The Role & Contributions of Hydraulic Testing Labs: Part IV, Modern Power Plant Studies

Hydraulic testing laboratories have played key roles in advancing the science, practice and teaching of fluid mechanics. One on-going laboratory has made far-reaching contributions in the field.

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With the increased size of the power plants came problems related to the intake and discharge of condenser cooling water systems. Concerns with intake and discharge structures relate to their hydraulic behavior. In terms of power plant operation, these potential problems can be categorized into three areas: outside the intake structure, inside the pump sump, and outside the discharge structure.

Flows approaching pump intake structures are sometimes the source of pump problems in intake structures. The design of a pump sump can be invalidated because of the flow patterns outside the structure. Flows going by the structure (such as river flows going by perpendicular or at an angle to the intake) can cause swirling flow in front of the intake screens that can reduce the effective area of the intake. Channels with similar approaches can also have the same effect.

Sometimes the problem lies just inside the structure, in the screen area. Contractions and/or expansions in this area may cause the start of eddies in the pump well, resulting in rough and inefficient operation of the pumps. Alden Research Laboratory (Alden) conducted one such study in 1972 for the Bridgeport Harbor Electric Station in Connecticut. The condenser cooling circulating pump had severe vi-

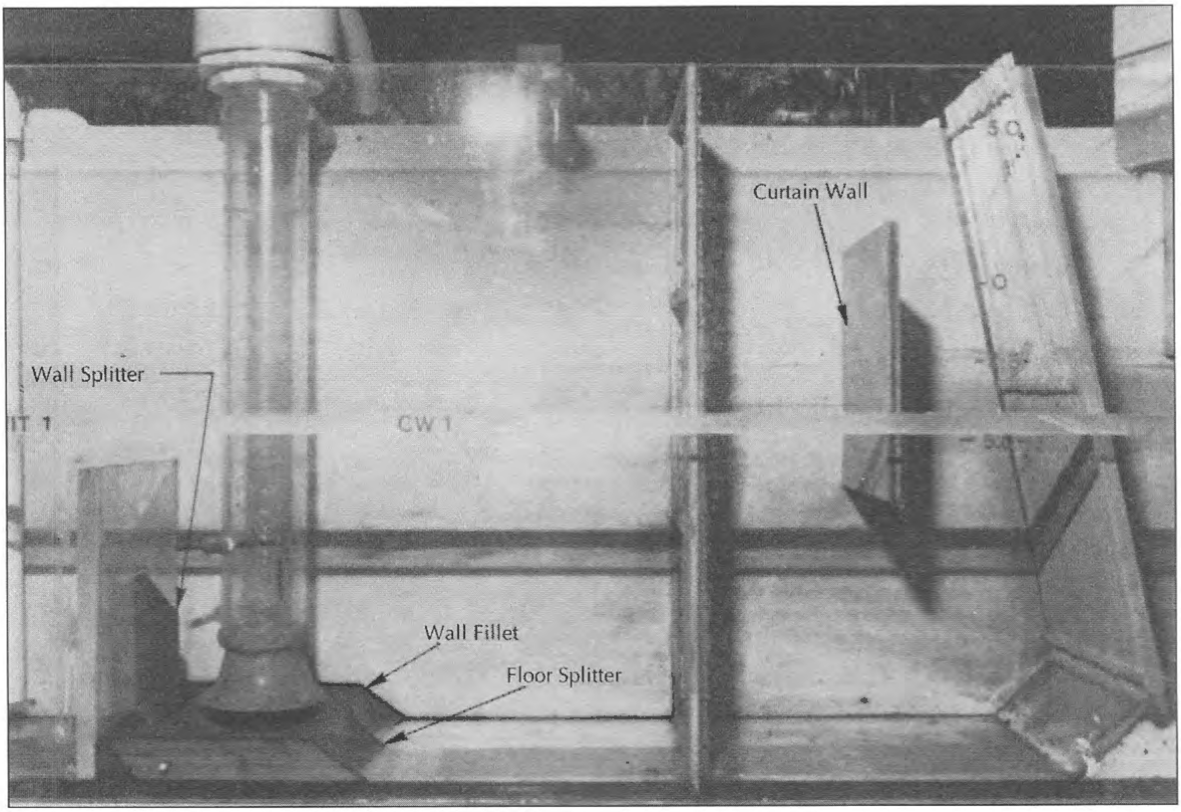

FIGURE 1. Pump intake sump with modifications.

bration problems accompanied by large suction noises. The sump was 15 feet wide. However, rotating trash screens had been installed, some of them 29 feet ahead of the pump. These screens required the flow to turn 90 degrees to go through the screen and then turn another 90 degrees after passing through the screen. As the result of this design, the flow width through the trash screen mounting structure was reduced to 3.5 feet, with velocities of around 10 feet per second approaching the pump at the center of the sump. Large, unstable vortices formed on both sides of the sump, entraining air at random intervals into the pump. The remedy was a baffle structure containing a screen with a 32 percent opening located 6 feet downstream of the screen structure. This solution was easily installed in the field, and pump vibrations ceased.

Prior to the construction of mega power plants, pumps and pump sumps were relatively small, and a number of so-called standard sump designs worked satisfactorily for most applications. However, problems began to appear with the "standard" sump designs when the pumps were made bigger, vertical pump columns increased in length and sumps were built larger. The problems were usually in the nature of large intermittent air-entraining vortices that caused poor pump performance or pump column vibration, or both. With multiple pumps in the same sump, it was not rare to also see horizontal vortices from one bellmouth to the other. In some cases, the vibrations were so severe that the pump column experienced structural failure.

In general, the sumps tended to be too large. Besides reducing the size of the sump, many other changes were sometimes necessary to solve the problems. In the case of the Indian Point (New York) Nuclear Power Station, Unit 3, cooling water intake (tested in 1985), changes to the original design included splitters under the bellmouth, corner fillets around the three sides of the pump, a curtain wall and a change in the floor configuration. These modifications have been designed into many and backfitted into others (see Figure 1). It should be pointed out that sump changes such as these are not easily made to existing structures.

Alden found a niche in pump intake studies. A few organizations and college laboratories performed this type of study, but many other college hydraulic laboratories found the projects to be too routine or unrelated to "research." To Alden's benefit, these pump intake studies often led to the laboratory conducting other projects for utility companies. The relationships that developed continued for years and decades. Most importantly, the basic knowledge Alden gained from these studies allowed the laboratory to build an expertise for very large future projects.

Model studies were also performed on many service water pump sumps. Their problems and solutions were identical to condenser cooling water pump sumps. Therefore, model testing during the conceptual stages for any pump sump configuration was not only beneficial, engineering-wise, but also economical in the long run.

Open channel discharges from condenser cooling water systems can also be sources of problems. Recirculation, erosion and dilution are all factors that might have an effect on a project. Recirculation, in some cases, has been minimized by discharging along the shoreline of a river so that the water clung to the bank (called the Coanda effect). This setup increased the distance from the intake before the flow separated from the shoreline.

Not all cooling water systems utilized natural once-through cooling water from lakes or rivers. In some large plants, mechanical or natural draft cooling towers were used, and models of these pump intake structures were tested. In cooling tower models, the pump sump was modeled with a sufficient portion of the tower's basin. Water was distributed in the basin using a perforated plate simulating the cooling water flow at the bottom of the cooling tower. Data acquisition was similar to other pump sump studies and utilized a visual classification of vortices as well as a swirl meter (see Figure 2) to record data. One study performed by Alden had horizontal pump intakes that differed from most of the other intake studies, which tended to have vertical pumps. The solution to this problem involved the use of a vortex suppressor located above the intake. Doing many studies like this permitted Alden to develop a stockpile of many standard pump bells and model components, leading to project efficiency.

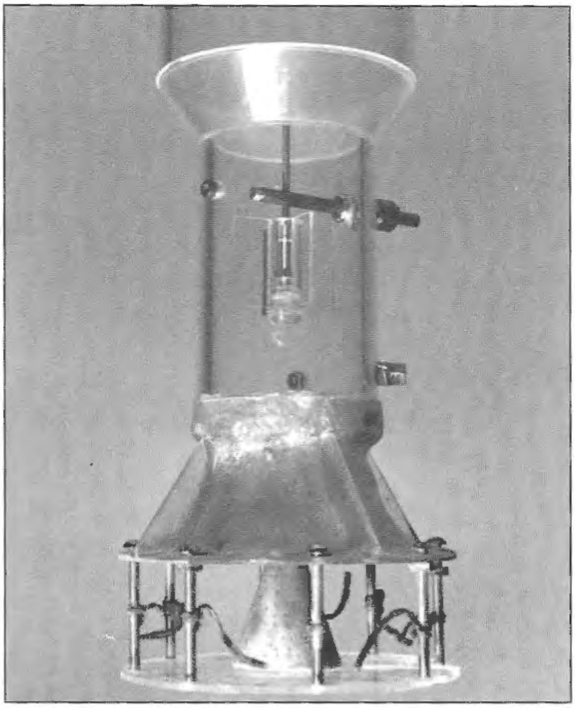

FIGURE 2. A swirl meter in a pump column, with yarn streamers used for flow visualization.

Emergency Core Cooling System Pump Sumps

Pump intake studies were not always related to circulating water-condenser systems. Some pump intake studies were on critical safety components in nuclear plants. In the mid-1970s, the Nuclear Regulatory Commission (NRC) became concerned about the reliability of the emergency core cooling system (ECCS) sumps located in the reactor containment building. In the event of a loss-of-coolant accident (LOCA), this ECCS and the containment spray systems (CSS) would be activated to supply coolant to the reactor core and vessel to dissipate the decay heat (to prevent core melt) and to the CSS to reduce containment pressure (to minimize atmospheric releases). Initially, these systems drew water from a large supply tank. Later, the water that accumulates

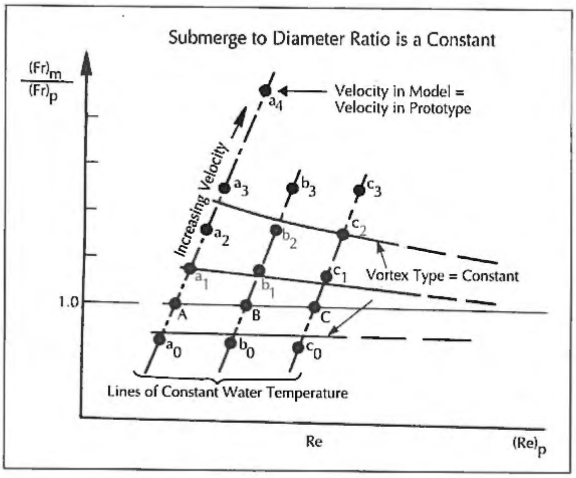

FIGURE 3. Vortex projection graph.

in a containment sump was recirculated (pumped) through the system. In effect, the ECCS sump was similar to any other pump intake, except poor performance due to excessive vortex activity could have very severe affects on reactor cool-down. There were basically two flow-related issues for the NRC:

- The ECCS sump had to be designed so that the intake was basically vortex-free with no air entrainment. (With air in the pumped flow, the ability of the flow to remove heat would be reduced.)
- There had to be sufficient submergence on the inlet to the pump so that the operational performance of the pump, particularly flow, was not impaired due to low net positive suction head (NPSH). (Sufficient head was achieved by using various combinations of blocking the approach screens to the sump.)

The crux of the matter was that these problems, with any of the various combinations of screen blockages, could not be addressed analytically. Furthermore, because many nuclear plants in the United States were site-specific designs with little standardization, the performance of one ECCS sump could not be confidently extrapolated to anther plant. Much later, the issue of debris injection would become a concern.

Trying to prove that the actual existing sump was functional was analogous to checking to see if a specific water sprinkler in a fire sprinkler system would operate during a fire. In 1977, a client visiting the laboratory on another study posed this question to George E. Hecker (who had succeeded Lawrence Neale as Alden's director on November 17, 1975). Hecker indicated that he would look into the possibility of model testing.

After a study of the existing literature, a proposal was made to use a new vortex projection technique. This vortex projection technique with a large model scale was required at the time because:

- a high margin of safety is required in nuclear-related work, compared to more routine vortex testing at pump intakes; and
- the scaling of vortex phenomena was affected by the Reynolds number, which basically considers the inertia of the flow compared to any damping due to the water viscosity.

Viscosity is affected by water temperature while the model velocity is affected by the linear scale selection. These are called "scale effects," and the NRC was concerned because physical modeling of these systems was unprecedented. For the vortex projection technique, tests were carried out at four different water temperatures with a number of different flow rates at each temperature. These flow rates simulated Froude numbers above and below that of the prototype. (The Froude number is the ratio of the inertia force to the gravity force.) A plot of Froude number versus Reynolds number was then constructed, and the vortex intensity number indicated at each test point. Loci of vortex intensity number were plotted on the curve (see Figure 3). The prototype operational Reynolds and Froude numbers were then put on the graph, and the loci lines extrapolated to obtain the vortex intensity expected in the full size prototype.

This technique was first utilized on a model of the ECCS sump for the Three Mile Island Nuclear Plant ECCS sump. The model was geometrically identical to the prototype, including all significant piping and any structural members or flow-interfering structures. Tests were conducted to study the system in the recirculat-

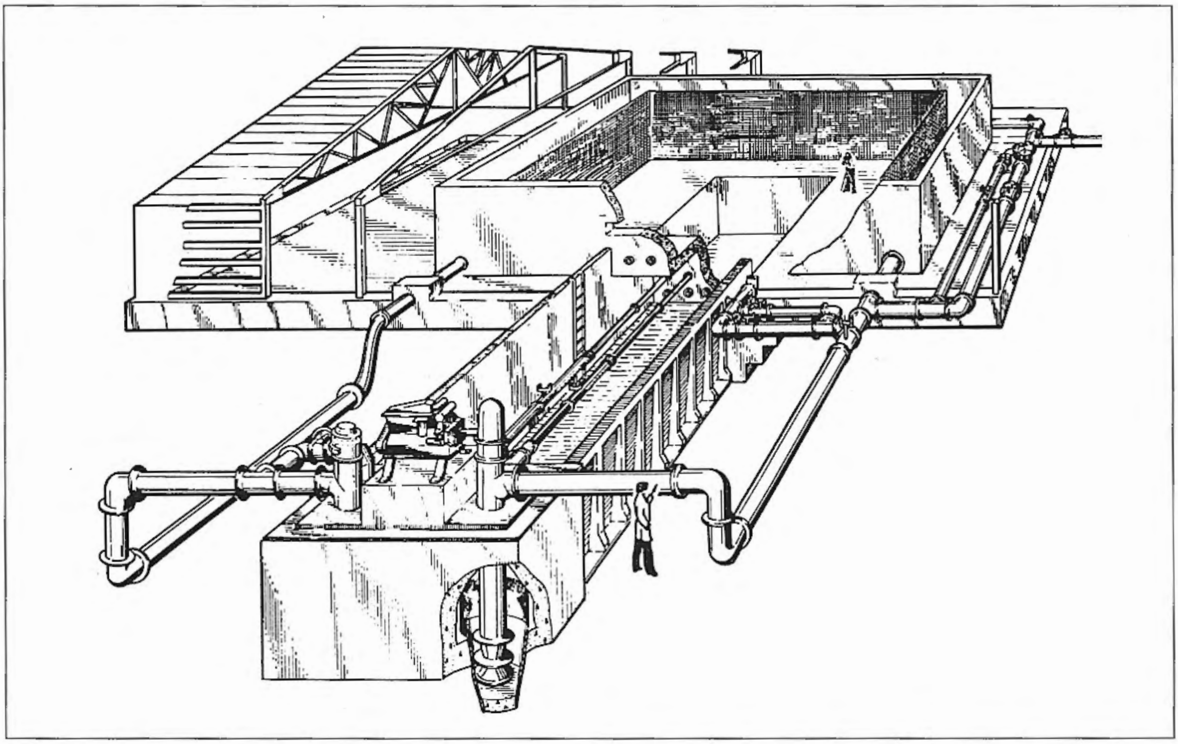

FIGURE 4. Facility for containment sump reliability studies.

ing mode. Vortices were evaluated visually, and vortimeters were used to measure prerotation in the intake piping. As in many of these studies, one or more horizontal layers of bar gratings suppressed vortex activity. The report was presented to the NRC and was accepted as a method to predict that the sump would perform as designed.

Once the word "got out" that the NRC had accepted the report, the flood gates opened and many other studies were commissioned. Because of the similitude concerns, the model scale on all tests was between 1:2 to 1:4 (one study had a full-scale model). None of the scale models duplicated the full 360 degrees of the containment vessel. Depending on the complexity of the interior of the sump, only 90 to 180 degrees of the vessel was modeled.

Full-Scale ECCS Testing

Although the models seemed able to predict emergency sump performance, there was still some question about the scale effects related to the Reynolds and Weber numbers (the latter is the ratio of inertia force to surface tension force). Laboratory staff also wanted to develop general design and review criteria that could be appplied to all plants. To resolve these NRC issues, Sandia National Laboratories contracted Alden in 1980 to build a million-dollar test facility to evaluate the vortex problem using different sump parameters in a full-scale setting. Testing continued until 1983.

The containment sump reliability (CSR) facility (see Figure 4) was designed to permit easily varying geometric and flow parameters with simple alterations of floors, walls and pipe fittings. The facility consisted of a 70- by 35- by 12.5-foot high concrete main tank and a concrete sump tank measuring 20 by 15 by 10 feet high situated within the main tank. Inflow into the main sump was through three sides of the main tank. Non-uniform flow was simulated by blocking any or all portions of the three-sided inflows. Four horizontal rows of outlet holes were located on the front wall with each row having five 25-inch diameter holes on 4-foot centers. Suction pipes ranging from 8 to 24 inches in diameter could be accommodated in each opening.

The suction pipes extended from the sump tank to a suction chamber 50 feet away.

Equipped for testing, the pipes contained a flow meter, a swirl meter, an air void fraction meter and a series of ten pressure taps located at 1-foot intervals along the pipe to measure the pressure gradient. Maximum flow for the facility was 20,000 gallons per minute (gpm). The facility was also equipped to simulate pipe breaks to investigate water jet impingement in the sump. Maximum impingement flow was 12,000 gpm. Data acquisition was by means of a mini-computer that received visual information on the vortex intensity and location information from a hand-held terminal and electrical signals from the instrumentation in the suction piping.

The main areas of concern in the studies were:

- *Entrained Air.* This air could be from surface vortices, air entrainment from pipe break jets or dissolved air coming out of solution as the result of fast swirling flow in the intake piping. (This was possibly the first time in the world that air content had been measured in vortex type studies.)
- *Prerotation.* Prerotation due to screen blockage or non-uniform approach flow patterns could have the effect of increasing the pressure loss in the inlet piping. Prerotation also can be a cause of reduced pump performance.
- *Excessive Losses in the Sump & Pump Inlet Piping*. This can lead to insufficient NPSH, thereby causing the pump to cavitate and reduce flow.

The main test program involved 66 configurations of pressurized water reactor (PWR) sumps and four configurations of boiling water reactor (BWR) sumps. Some of the configurations had horizontal pump intake pipes while others had vertical intake pipes. Tests on each configuration were made using a range of intake flows and water depths. In total, some 600 individual tests were performed.

This study also investigated different types of physical vortex suppressers. The use of horizontal gratings above the pump intake piping and grating cages with relatively wide grates were found to prevent air entrainment due to vortices. For existing sumps of all sorts, this approach could be suggested as an economical means of solving a vortex problem.

The basic results of all the scaled and unscaled testing showed that in vortex modeling, the viscous effects were negligible if the Reynolds number was greater than 70,000. This conclusion supported other findings that viscous scale effects on vortices were small when the Reynolds number exceeded 30,000. Also, no vortex problems were likely to be encountered when the inlet Froude number (based on submergence) was less than 0.23. (It is interesting to note that a similar Froude number value had been determined in 1979 based on numerous final designs for pump storage intakes that had been modeled at Alden.)

Screen Blockage Testing

Because of the potential for screen blockage due to insulation that could be blown by pipe break into the flow approaching the sumps, Alden received inquiries to study the hydraulic behavior of many types of pipe insulation used in nuclear plants. The number of such studies was increased by the intense competition between the various insulation manufacturers and the large head losses that could potentially occur at a screen.

The studies were essentially of three types:

- One question related to the pressure loss through the insulation as it accumulated on the screens. These studies were essentially performed in a closed pipe loop where shredded insulation was introduced into the system and was caught on a screen. The pressure drop across the screen was continually measured to monitor the pressure increase with time as the insulation continued to pack on the screen. The effects of temperature and water alkalinity were also investigated in this facility.
- A second type of study was conducted in a facility originally constructed to study fish behavior. In this full-scale facility, the movement of shredded insulation of different sizes was observed. Velocities required to move the insulation were also recorded.
- The third type of study involved finding the minimum velocity needed to break down the various insulation packages. In

this study, a water jet from a nozzle was aimed at the insulation, and the jet velocity was increased until the insulation showed signs of initial failure. The velocities were further increased until particles of insulation were blown away. This information of the breakdown of insulation packages was required to predict how particular insulation would stand up under jets formed by accidental pipe breaks.

Condenser Testing

Alden was involved not only in studies related to the intake and discharge of condenser cooling water systems but also in a number of different types of condenser studies. In the early 1960s, Alden modeled a horizontal split condenser. The condenser had rectangular approach piping with two right angle elbows in different planes just ahead of the condenser inlet. Observations in the field indicated that the condenser tube bellmouths in approximately the center of the two tube sheets were completely eroded. In addition, the tube sheets in those areas were highly polished.

The condenser was modeled in plexiglas to observe the flow patterns inside the condenser. Punched paper dots from computer cards were used to visualize the flow. The tube pattern was modeled with one tube in the model representing ten tubes in the prototype. The length of the tube was not modeled, but the pressure drop through the tube was modeled by inserting orifices in each model tube. To duplicate the reduced pressure in the prototype, the model was placed at the top of a 20-foot tower and the flow was supplied from a low pressure pump located at the ground level.

Initial tests immediately revealed a high velocity vortex at the center of the condenser extending from one tube sheet to the other in the same area where the damage occurred in the prototype. The vortex was so strong that it pulled air out of solution, and the model core contained only air. After numerous tests, a solution was obtained consisting of two perforated plates installed to split the condenser in the form of a tent. The holes in the 1-inch thick plate were 2 inches in diameter.

The next condenser study was another model of a horizontal split condenser (see Figure 5). The model construction was similar to the first study, but no attempt was made to model the pressure in the condenser. Visual and photographic documentation was used as before. However, three-dimensional velocity probes had become available in the decade between the two model tests. Such a probe was utilized to obtain the velocity distribution just in front of the tube sheet.

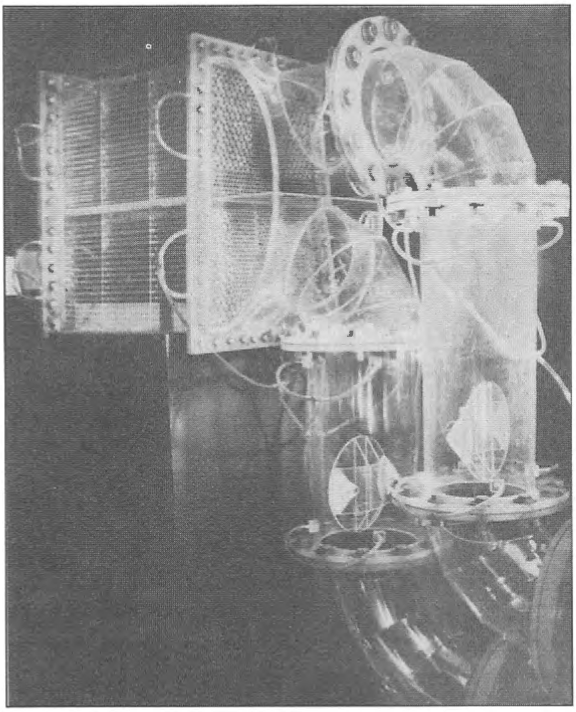

FIGURE 5. A condenser model.

A major breakthrough in velocity measuring instrumentation came in 1978 with the Hope Creek (New Jersey) model of a two-pass horizontal condenser. Tubesheet erosion and flow distribution were the concerns in this study. Flow visualization was accomplished as in the other studies. Velocity measurements, however, were obtained by use of a laser doppler anemometer (LDA) system mounted on a converted milling machine base. The LDA system works on a doppler shift principle using a helium-neon continuous wave laser. The laser beam passes through a beam splitter, creating two equal beams. The beams are then positioned to intersect at a desired focal length. At this intersection, called the measuring volume, the beams interfere constructively and destructively, producing fringe patterns in the measuring volume. Particles, no matter how small, cause the fringes to move, creating a doppler shift. The light reflected by the particles results in a shift in frequency that is a function of the velocity of the particle. A photomultiplier detects the movement of the fringe pattern and feeds that information to an automated data acquisition system.

Condensers, fouled by biological growth, have reduced heat transfer, thereby resulting in reduced power production. One method to counteract this buildup is to periodically inject the condenser with a dose of chlorine. This method kills the organisms, and they get flushed out with the condenser cooling water. In the late 1980s, with environmental concerns for the water bodies receiving these condenser cooling discharges, the U.S. Environmental Protection Agency passed a new regulation that limited the total discharge of residual chlorine to 0.2 mg/L for no more than two hours per day per plant. This regulation prompted utilities to investigate other means to prevent or remove fouling. Studies, based on a prior Salem (New Jersey) model, were conducted using fixed nozzles to selectively inject chlorine upstream of the tube sheet. This technique, called targeted chlorination, injects chlorine through a pipe with a nozzle at the end. The pipe is located far enough from the tube sheet so that the flow expansion from the discharge chlorine jet covers a portion of the tube sheet. The study was used to minimize the number of nozzles necessary to ensure that all the condenser tubes received enough chlorine to effectively remove the fouling.

Finally, evaluations of ball distribution in a sponge ball condenser tube cleaning system were conducted in the Salem model. The sponge balls were modeled with 0.125-inch-diameter colored fiber decoration balls. At the outlet to the condenser, a basket-type container (which was partitioned off in different sections) was used to catch the balls so that the percentage falling in each section of the basket could be obtained. To decrease the test time, different colored balls were used for each test, requiring the unbolting of the downstream end of the condenser only after a series of colors had been used.

Detailed studies of the inlet flow in the vicinity of the inlet of the condenser tube were made using a 3-inch inside diameter model tube to represent a 0.902-inch inside diameter prototype tube. The use of metal inserts was also studied in a similar model. In both cases, flow patterns and pressure losses were obtained.

When condenser tubes began to leak, either the inserts were installed, an epoxy coating was used temporarily, or the tube was plugged. The method of applying the coating and the behavior of the coating under vibration were studied at Alden. A wide assortment of plugs, made of different materials and varying in cost, were tested under different pressure conditions to determine their holding power. As in the past, one study would lead to another in an effort to improve the performance of power plant related equipment.

Although not related to power plants, a condenser and a hotwell on board a ship were modeled to investigate the behavior of the condensate under oscillating conditions. The model was mounted in a cradle at the end of a arm pivoted 17.5 feet away. The cradle itself was pivoted 12.48 feet from the arm. This permitted the maximum pitch to be ±15 degrees and the maximum roll to be ±50 degrees. The whole system was operated by piston cylinders controlled by an electronic control system. Data acquisition was by a video camera mounted on the cradle.

Video cameras became a great asset in model testing. Prior to videos, still photographs were taken to show customers some of the results of the tests. At regular time intervals, the client came to the laboratory and was shown a number of significant tests during the visit. These visits were always stressful times for the laboratory staff. The scenario usually went like this:

> The customer arrived early in the morning and was shown the model in one configuration. Afterwards, the director would take the client for coffee while the rest of the staff made a change to the model. The customer would return, see the model run under the new configuration and then to lunch with the director while the staff made another change. After lunch, there was a repeat of the morning's activities. By the end of the day, the customer had seen the model perform under four different configurations. In

some cases, the staff would even work that night to prepare the model for the next day. With a video camera, this extra activity was eliminated because all tests could be easily taped. In fact, a tape of a test today can be sent by special overnight courier and be viewed by many engineers the following morning in their own offices. The cost of a camera and tapes was much more economical time- and money-wise than a round trip to observe the tests in person.

Since Alden had worked almost since its inception with utilities, it was not unusual that it performed a number of studies on other fossil fuel plant equipment. Among some of these studies were:

- Hotwell outlet of a condensate polisher system;
- Water strainer comparison of pressure loss;
- Spray cooling nozzle design/efficiency;
- Air coolers;
- Steam separator drum in a condensate system;
- Boiler flow patterns investigation using water as the flow medium; and,
- Manifold pressure losses.

Stack & Three-Dimensional Air Modeling

Up to this point, all the above studies used water as the fluid. Other studies used air as the medium. Probably the first such study was a smoke stack study of the Edgar Station (Boston, Massachusetts) in 1954. There was concern about stack releases from the new Edgar Station because, surprisingly, objectionable ground-level concentrations had been detected 5 to 6 miles away. Another concern was that a south wind could direct smoke from burning high-sulfur oil toward Logan Airport. The purpose of the study was to evaluate the dispersion of smoke and test the effect of varying stack height, exit velocity, devices on the top of the stack and building streamlining. Smoke emerging from the chimneys and down-drafting locally to ground level was also to be investigated.

A 5- by 5- by 8-foot-long wind tunnel with velocity capability of 0 to 50 feet per second was built in Alden's low head laboratory for this testing. The 1:250 scale Edgar Station model duplicated every detail of the exterior features of the plant and was mounted on a 5-foot diameter rotating table to evaluate the smoke flow at every wind direction. The smoke was generated by vaporizing oil on electric heaters. Air was passed over the heaters, whose heat output could be varied, and distributed to a manifold. This manifold could distribute the smoke-filled air to the model smoke stacks and could bypass some of it to regulate the air flow to the stacks. Pitot tubes in each stack measured the air flow out of each stack. Photographs of each test were taken using strobe lights to stop the action. There was concern about the model's accuracy and applicable similitude requirements. It was concluded, based on observations of the operating prototype, that the model smoke was less buoyant than the prototype, and the model results were conservative.

By the 1960s, when very large steam-electric stations were being planned and air quality laws were coming into effect, the height of the stack became an even more important component of plant design that depended to a major extent on fuel type. Coal-burning plants particularly became concerned with local ground-level concentrations. These concentrations were reduced by stacks having heights of 800 to 1,000 feet. Mathematical modeling of stack releases became the norm. Various analytical models allowed consideration of various meteorological and atmospheric factors. To prevent downwash and local ground concentrations, some "rules of thumb" indicated that a chimney should not be less than 2.5 times the height of adjacent structures, subject to modification based on fuel type. Natural gas and low-sulfur oil plants had the least air pollution problems.

By the mid 1970s, it was realized that tall stacks, which basically put the pollutants in upper wind levels, were causing visibility and pollution problems hundreds of miles away. Restricted visibility at the Grand Canyon due to plumes from the Four Corners Power Plant, possible acidification of soils and lakes, deposition of heavy metals and other undesirable situations can result.

Three decades later, a stack-breeching section was investigated (see Figure 6). The tall stack did not have sufficient draft to discharge

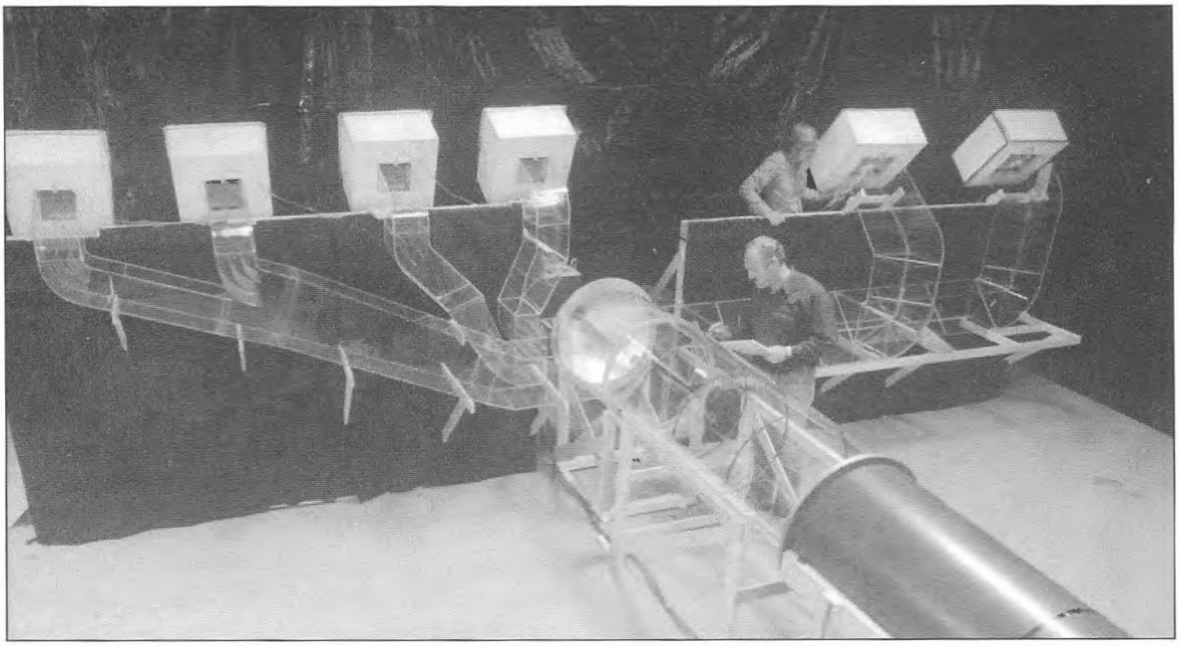

FIGURE 6. Model of ducts to a stack base.

the exhaust gases from two units. Inflow from each unit entered the stack at 180 degrees from each other. Flow into the plexiglas bottom of the model allowed the two gas streams to oppose each other and caused swirling flow to go up the stack. This swirling flow created higher pressure drop in the chimney, thereby resulting in decreased flow. The bottom of the stack was modified by putting in a splitter wall and some vaning. In addition, vaning was installed in the rectangular approach piping to further reduce the overall system pressure loss.

Three-dimensional air modeling would become a much larger activity in the 1990s when air regulations became much more stringent in order to comply with the 1990 Clean Air Act. Modeling of precipitators would also become routine. A typical air study on a wet electrostatic precipitator was performed with a model constructed entirely in plexiglas. It investigated the approach and the discharge flow patterns within the precipitator. The main objective was to better the efficiency of the precipitator by improving the flow patterns. Greater efficiency was achieved without increasing the overall length of the precipitator through vaning and using a series of perforated plates.

Smoke was considered to show the flow patterns in the stack-breeching model. However, the quantity of smoke necessary in a 3-foot-diameter model stack would have been excessive and would have caused problems in the immediate environment. Someone at Alden thought of the movies and talked with movie equipment distributors. They sold a system that produced "smoke" by means of neutral density helium bubbles. A system was acquired and used successfully to obtain photographs of the flow phenomena in the model.

The same flow visualization system was used to study a superheater manifold. The aim of the study was to equalize the flow out of each part of an existing manifold that was causing many field problems.

Warm Water: Thermal Model Studies

The first large hydrothermal models built by Alden were constructed in the early days of environmental concerns. Some were built to study recirculation while others were dictated by the loose environmental regulations of the time. In some cases, these regulations seemed to be more in the minds of the regulatory agency personnel than on paper. Many meetings were held with utility and regulatory agents to review model test results (usually surface isotherms) to see if the intent of the regulation was met. In many cases, it was a judgment call based on what people thought the regulation meant.

In 1967, Alden studied the thermal discharge effects of the proposed Easton Nuclear Plant on the Hudson River. A Venturi-type discharge structure, with a throat velocity of 10 feet per second, was placed at the end of a discharge channel to maximize dilution and to prevent fish from entering the channel. This structure was called a hydraulic fish screen. By today's standards, it was a primitive surface jet discharge (thermal diffuser) where the intent was to rapidly entrain cooler river water to quickly reduce the temperature and extent of the discharge.

The Herbert A. Wagner Plant on the Patapsco River in Maryland had a similar high velocity discharge (13 feet per second at low tide) at the end of a short discharge channel. This study aimed to prevent recirculation and minimize the heated water from the Orchard Beach-Riviera Beach areas. Prior to the study, field tests were done at the site to obtain near-field velocity information. The velocities were obtained by using floats with metal drogues and photographing the floats at different time intervals from an airplane. After the floats had been deployed, Alden personnel went to the roof of the plant to observe the floats and to make notes regarding the tests. Suddenly, as if out of nowhere, a high-speed motor boat appeared, scooped up two of the floats and went on its way as people screamed from the roof. It was the second time in this type of study that floats had been damaged or stolen. Once before, on the Hudson River, floats had purposely been run down by a barge captain, who agilely guided the barge tow directly over the center of two floats as Alden staff watched helplessly.

Not all discharge structures were at the end of channels located near the shore. In 1969, Alden tested an offshore discharge structure for the D.C. Cook Plant on Lake Michigan that would minimize mixing. The idea of this scheme was to maximize the surface water temperature so that the thermal "driving force" to the atmosphere would be the greatest. This thermal transfer was accomplished by discharging through two 90-degree elbows at the bottom of the lake. The model was constructed in a small tank, and the elbow was made in two parts of fiberglas laid up on a wooden mold.

The D.C. Cook plant was caught in the changing regulatory climate. In the fall of 1970, the plant was informed that the temperature exposure for biota entering the heated plume had to be minimized. Consequently, a structure that produced maximum dilution was preferred over a discharge with a minimum dilution. Maximum dilution was best achieved with a jet-type discharge structure at the elbow locations (see Figure 7). A minimum size area enclosed by a 3°F isotherm and minimum shoreline temperature were required, which was accomplished using a 1:75 undistorted near-field/intermediate-field model. A multi-slotted discharge structure was developed, and the maximum surface and shoreline temperatures were greatly reduced.

The 1:75 D.C. Cook model built in 1971 was the first of the so-called "piggy-back" models. When many of the first large models were completed, clients requested that they be kept intact in case future studies were required. The customer would pay a small rental fee for that privilege. When contracts for other large models were signed, Alden faced the dilemma of where to build them. Since the models required enclosed buildings, and all the land near the main buildings was occupied, it was decided to build these new models above existing models in such a way that they could easily be taken out. (This scheme was never put to the test since removal of any of the top models never took place. However, in some cases, the lower model basin was used to supplement the sump in the building.)

The "piggy-back" models were those containing gently sloping topography, such as ocean and large lake sites. By the late 1960s, virtually all thermal models concerned with mixing were constructed having the same horizontal and vertical length scale (*i.e.*, an undistorted model). The platforms usually consisted of wooden 2- by 12-inch templates, set at the proper grade to represent the topography, sitting on metal pipe stilts. The D.C. Cook model used a type of cloth or screening stapled on top of the templates, which was then sprayed with chopped fiberglas and epoxy to give the model a hard surface. Unfortunately, the material sagged between the templates, causing a rippling topography. Consequently, much work was required to fill in the sags and properly re-

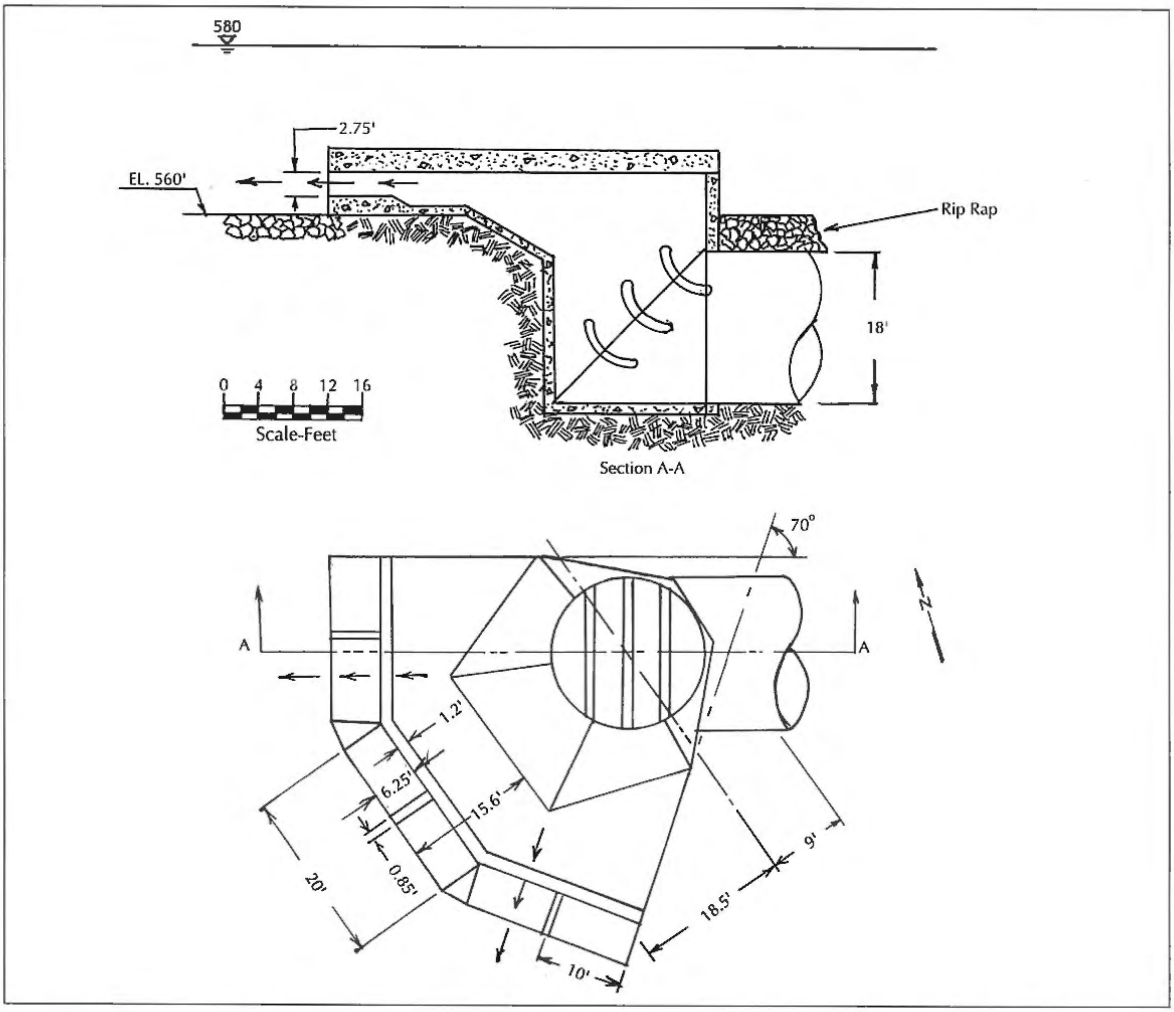

FIGURE 7. Slotted jet discharge structure for the D.C. Cook Plant hydrothermal model study.

produce site topography. A lesson was learned and, in the future, 0.25-inch-thick plywood sheets were put on top of the templates and then coated with the fiberglas. At least seven models were "piggy-backed" in the 1970s and 1980s using this technique.

Fiberglas thermal models were thermodynamically desirable compared to concrete-topped sand backfilled models. As the tests became more sophisticated, heat transfer to the model's surroundings became an issue. A fiberglas model absorbed and conducted away less heat.

Hydrothermal Regulations

The simple diffusers (as in the Wagner and D.C. Cook models) served their purposes, but things would soon change. In the late 1960s and early 1970s, many states began promulgating stricter regulations regarding thermal discharges. It was not always simple to write a regulation that would encompass all of the water bodies for a particular state. Few states had such a simple regulation. Some states had different regulations for fresh and ocean waters. In many cases, the regulations were somewhat site-specific based on the ecology of the area. For example, a river originating in the mountains and discharging into the ocean might have one regulation for the river source to the bottom of the mountains, another from that point to the upper reach of the tidal effects and a third regulation from that point to the ocean.

Tighter regulations put an end to most of the economical on-shore or near-shore condenser cooling water discharges. Instead, cooling water system designers had to concentrate on offshore intakes and discharges, mixing zones and areas in the discharge water body beyond which certain temperature rises above ambient temperatures could not be exceeded. The industry's solutions were either off-shore, multi-port diffusers or cooling towers having no off-site thermal discharge.

The main background information for this work originated in the time period during which Alden started the major hydrothermal studies (roughly 1958 to 1964). Technical papers of that period mention mixing in tidal estuaries, turbulent jet theory, diffusion of sewage discharges, turbulent entrainment in stratified flow, discharge of warm water jet, turbulence in a diffuser boundary layer, convective currents in water and other related topics. By 1971, Dr. Donald R.F. Harleman and his colleagues at the Massachusetts Institute of Technology (MIT) were doing research and publishing technical papers specifically related to condenser cooling water discharges. The subject was of such importance to the utilities that one commissioned Drs. John E. Edinger and John C. Geyer, of Johns Hopkins University, to do a study of "Heat Exchange in the Environment."[1] The report was a textbook designed to assist engineers and scientists in computing temperatures related to the heating and cooling of natural water bodies.

By 1969, Alden had started a hydrothermal study of the Yorktown Station in Virginia that included a distorted overall model to obtain temperatures in the York River, and an undistorted model to study a multi-port diffuser for the existing and expanded plant. The overall model of the York River extended from the upper reach of the tidal effects at West Point, Virginia, to its mouth at the Chesapeake Bay. Major innovation was taking place.

Innovation in Thermal Modeling & Diffusers

It was during the mid- to late 1960s that physical thermal modeling techniques were extensively evaluated by Alden staff. A visiting mechanical engineering professor from Sweden, Peter Larsen, was a leader in this effort.

By the time the Yorktown model was built in 1971, Alden had added sophistication to these models, which in the early years were concerned with near-field mixing and far-field heat transfer. Temperature data acquisition systems using mini-computers replaced the old data recorders. Environmental controls were installed to keep the ambient air temperature in the model building constant. The idea of this system was to minimize heat transfer either into or out of the model. The goal was to control the atmospheric conditions at the equilibrium temperature — *i.e.*, the temperature at which no heat exchange occurred between the water and air. Sprinklers were mounted on the roof to reduce convective and radiant heat transfer to the model.

The intent of all hydrothermal models was to study only the plant heat discharge on a constant temperature body of water, exclusive of meteorological effects. This focus could be especially difficult to achieve in tidal conditions where numerous tidal cycles were required to establish "steady-state" thermal conditions.

The similitude of the model heat transfer with the prototype was a major concern that was extensively investigated during several studies. For one proposed project, model temperature isotherms were adjusted based on an existing plant's thermal isotherms and meteorological conditions in the field. In essence, the model was thermally calibrated. As part of the Indian Point (New York) thermal study, heat transfer pans were installed at the site and basic data were obtained. Heat transfer coefficients were also determined using pans floating on the pond adjacent to the rotating boom.

Special heat transfer pans were designed and built to monitor the actual atmospheric effect on the model and, in the early years, to determine the surface heat transfer coefficient (see Figure 8). These metal pans, which evolved over time, consisted of a continuous water labyrinth with one pan heated by coils located underneath it and an adjacent, unheated pan. Using the change in temperatures between the pans and the thermal inputs, heat transfer coefficients were calculated. The metal pan was mounted in a wooden box, with insulation between the pan and the box to reduce the heat transfer from all sides except the open top. The water in the pan was gently moved by a simple rotating paddle. Measurements of electrical energy input into the coils, water tem-

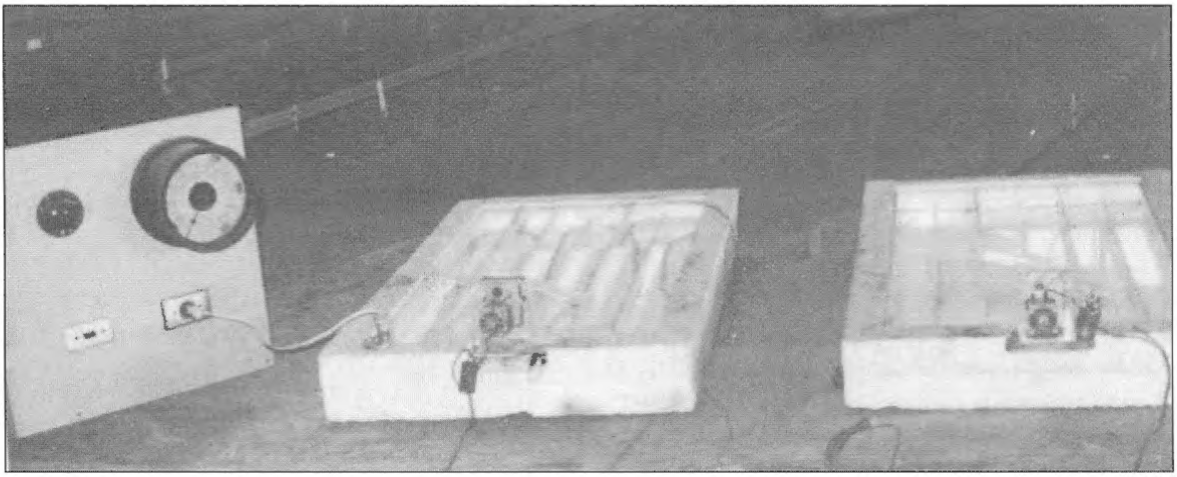

FIGURE 8. Special heat transfer pans.

perature, air temperature above the water, and wet and dry bulb temperatures were continuously monitored and recorded by the data acquisition and storage system. The wet bulb temperature was obtained by a "home-made" instrument consisting of a thermocouple inserted in a cotton wick coming out of a small bottle of water. A small fan blew over the wick with the required velocity as specified in the standards. The total effect was to continuously monitor and adjust the temperature of the ambient atmospheric conditions surrounding the thermal discharge. When steady-state conditions occurred to within about ±0.5°F, the test would begin by starting the thermal discharge.

As experience was gained in thermal testing, it was concluded that the pans could be simplified by eliminating the heating elements. The pans in effect became a monitor of atmospheric conditions in the building, and ambient water conditions were adjusted so that only the effect of the thermal discharge was measured.

The Yorktown diffuser for Units 1 and 2 was one of the early major thermal multi-port diffusers to be built in a tidal estuary where temperature would build up to a steady state over subsequent tidal cycles. The diffuser was built at a 30-degree angle from the shoreline, and contained ten 28-inch-diameter nozzles spaced 50 feet apart with a total diffuser length of 450 feet. The nozzles consisted of a simple elbow arrangement coming off the top of the diffuser and discharging flow at 14 feet per second horizontally approximately 27 feet below the water surface into the river. A second similar diffuser, which was 780 feet long with fourteen 42-inch nozzles spaced 60 feet apart, was also studied for a proposed Unit 3 at the same plant.

A cursory look at a thermal multi-port diffuser might lead one to believe that a standard design could be used for all such diffusers. However, local receiving water body conditions of currents, tides, bathymetry, plant flows, plant temperature rise above ambient, bottom materials and intake location all influence diffuser design. There are only three things that are more or less standard in a design:

- First, the water velocity at the exit of the nozzles should be in the order of 10 to 15 feet per second (preferably at the high end) to keep the momentum high enough to obtain good mixing. The upper limit is based on the economics of the size of the diffuser and nozzles and pumping costs, which increases at the rate of the square of the velocity.
- Second, the ratio of the nozzle area to the diffuser pipe or tunnel area has to be such that each nozzle discharges at approximately the same velocity.
- Finally, the optimum centerline distance of the nozzles from the bottom bed contour was determined in a 1973 Worcester Polytechnic Institute (WPI) master's thesis by one of Alden's graduate students, Robert Mattson, to be two nozzle diameters. At

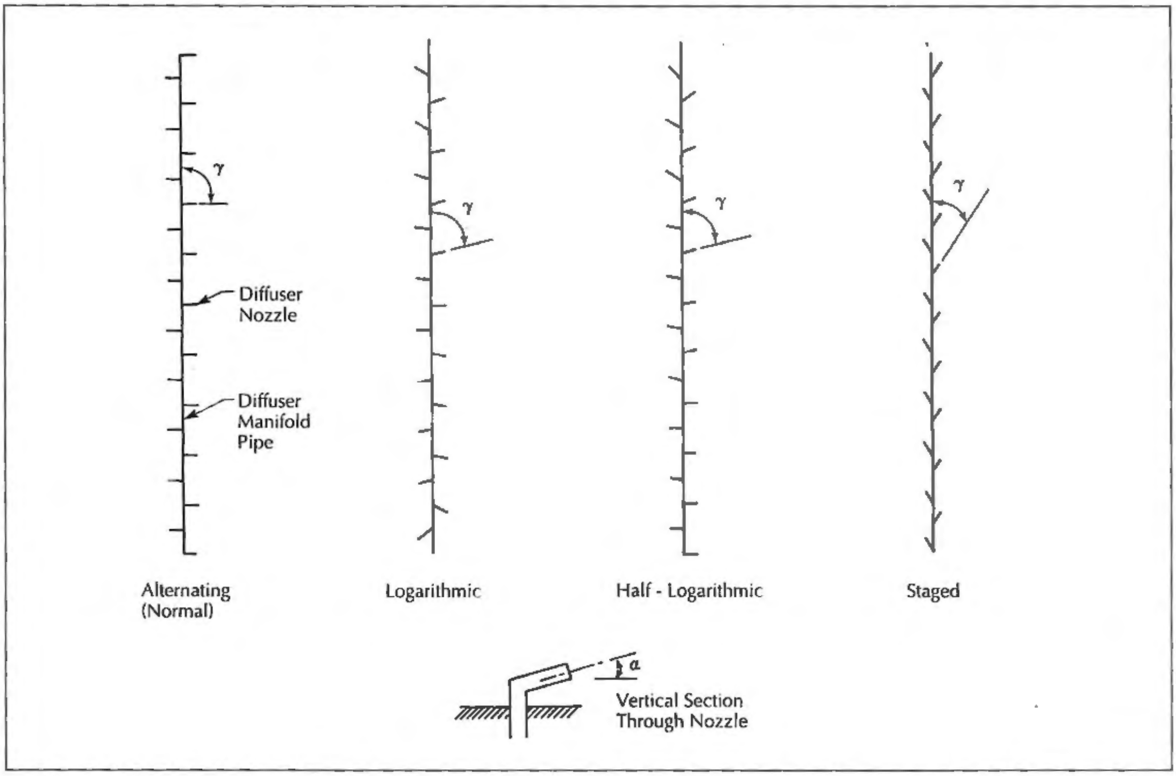

FIGURE 9. Diffuser nozzle orientations.

this optimum distance erosion cannot take place, and the jet should not cling to the bottom (causing reduced entrainment). Also, the nozzle must be oriented upward so that the high-velocity jet can entrain all the flow that its energy will permit.

Nozzles exiting from the diffusers can have many configurations. The basic ones studied at Alden were (see Figure 9):

- a 90-degree or more elbow coming off the top of the diffuser;
- horizontal or angled upward emerging from the centerline of the diffuser;
- a multiple nozzle riser off the top of the diffuser;
- staged diffusers having alternate discharging nozzles; and,
- slotted rectangular nozzles projecting from some submerged diffuser structure.

The latter was sometimes used to bring into compliance thermal discharges that were not "grandfathered" by new regulations.

An unusual situation occurred in 1972 with the Martins Creek Plant. The Delaware River Commission imposed thermal criteria for the plant, which was located on the Delaware River about 20 miles northeast of Allentown, Pennsylvania. Using a 1:25 model, a twelve-nozzle diffuser was developed. However, because the minimum submergence was only 2 to 3 feet, surface turbulence caused by the twelve jets was objectionable. To spread out the discharge and increase submergence, a 23-nozzle diffuser was situated perpendicular to the shoreline and followed the riverbed contour. The nozzles varied along the entire length and were also the shallowest at minimum river stage. The diameter of the nozzles varied from about 7.5 inches near the shore to 18 inches further out in the river (see Figure 10).

The first model to have a computerized printout of temperature rises above ambient was for the Indian Point Plant (Units 1 through 3). The model was tested along with the heat loads of the Bowline and Lovett plants, which are located in that portion of the Hudson River. A diffuser study for Bowline had previously been completed in 1971.

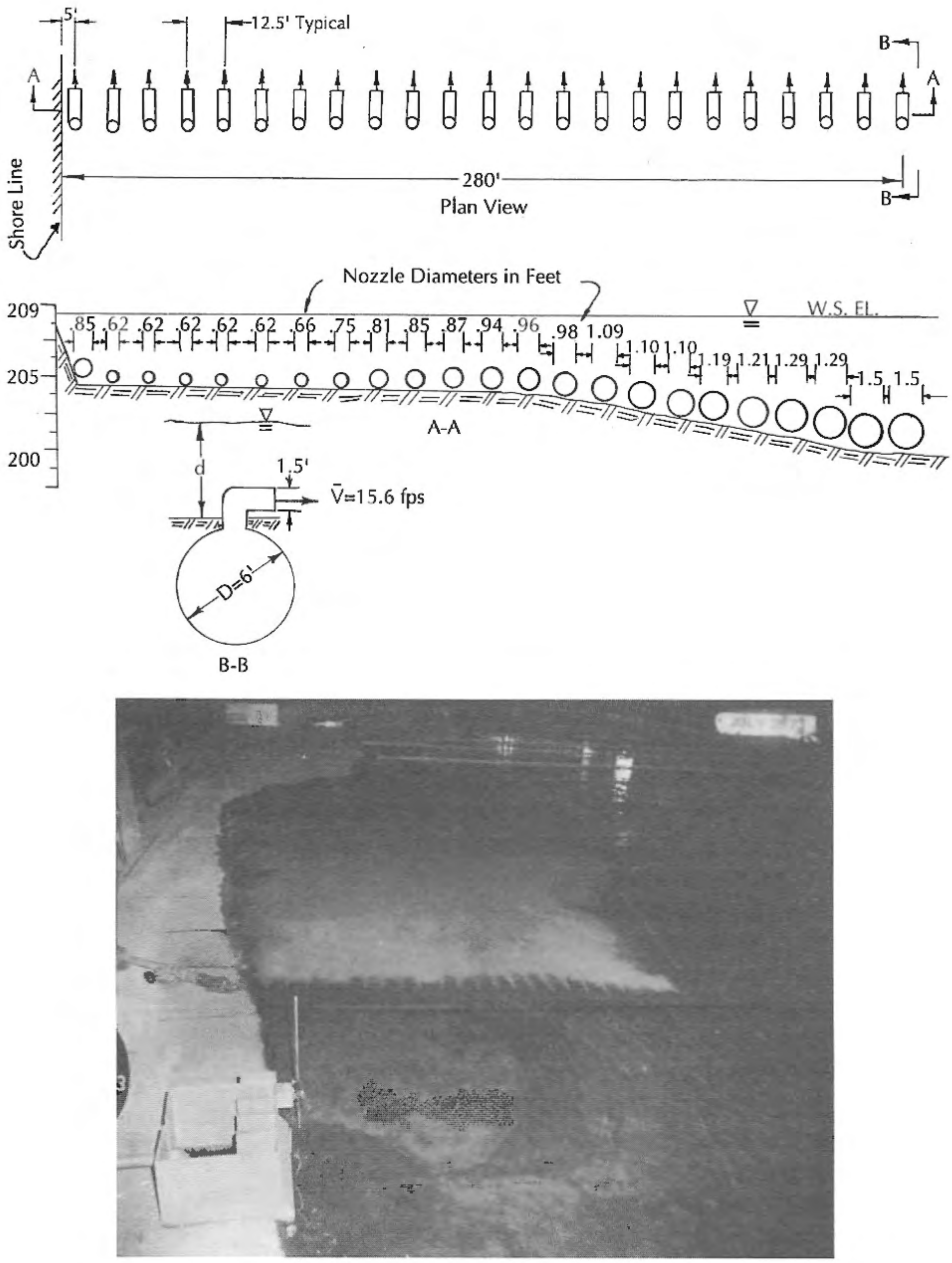

FIGURE 10. Martins Creek multiport diffuser.

A high-speed datalogger was used to scan all sensors in 17 seconds. The analog signals were converted to digital values of millivolts and were recorded either on magnetic or punched tape. Digital computer processing was used to convert the signals in degrees Fahrenheit, compute and then list temperature rises above inflow ambient temperatures. The computer also recorded temperatures throughout the model for five consecutive cycles at the same corresponding times in the tide cycle and averaged the temperatures for these five cycles. The data system had a resolution of ± 0.05°F and a repeatibility of ±0.15°F.

The New York State criterion for this section of river was that a temperature rise over 4°F should not exceed two-thirds of the surface river width nor over more than half of the river cross section. The criterion was satisfied with two diffusers — one for Units 1 and 3, and one for Unit 2.

The Units 1 and 3 diffuser was 850 feet long, had thirty-five 3-foot nozzles spaced 25 feet apart, and discharged flow at 10.5 feet per second. The Unit 3 diffuser was 600 feet long and had 25 nozzles with the same diameters and spacing as the other diffuser. Its discharge velocity was 11 feet per second. Both diffusers were situated at 45 degrees from the river centerline with the nozzles pointing downstream. What was peculiar with both diffusers was the angular variation of the nozzles to the diffuser. A logarithmic distribution of nozzle orientation along the diffuser was required to optimize lateral spreading of the effluent plume.

Studies involving typical power plants with diffusers having vertical risers containing multiple nozzles were conducted for the Fitzpatrick Plant in New York in 1969 and the Seabrook Plant in New Hampshire in 1977. Both plants had two nozzles per riser, with Fitzpatrick having a total of twelve 30-inch nozzles and Seabrook having a total of twenty-two 32-inch nozzles. One interesting aspect of the Seabrook nozzles was the original design. When a large-scale model of the riser with its two nozzles was first tested, it acted like a fluidic device. In a fluidic device, small pressure perturbations in the flow can cause the flow to shift from one port to the other. In the riser study for Seabrook, large amounts of flow would first emerge from one nozzle, then a short time later the large flow would leave the other nozzle. The alternating pattern continued periodically through the test. After it was confirmed that the inflow into the model riser duplicated that expected in the field, the riser containing the two nozzles was redesigned to eliminate the alternating phenomena.

One of the more intensive physical studies of diffusers was performed in 1978 for the proposed Jamesport Nuclear Power Plant in New York. The plant (to be located on Long Island Sound but never built) had a restrictive thermal criterion of not exceeding 1.5°F outside a 500-acre zone. The study looked at nozzle orientation, diffuser length and diffuser performance. In the orientation study, tests were run with alternating nozzles, a logarithmitic distribution, a half-logarithmitic distribution and a staged diffuser. It was concluded that a long staged diffuser resulted in a smaller mixing zone.

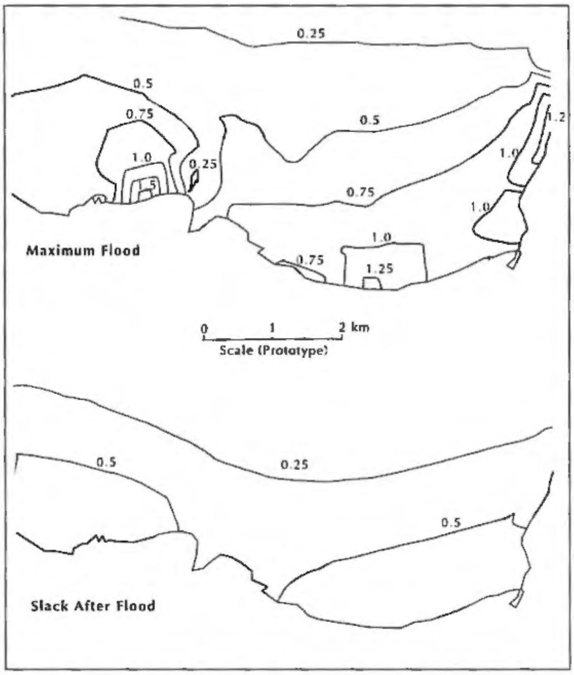

FIGURE 11. Background temperature rise isotherms.

The last very large hydrothermal physical model was built in 1986 for a power plant in Taiwan. This model had over 700 thermo-couples, and the comprehensive study also included mathematical modeling to study background temperature buildup at the site (see Figue 11). Near-field plume analyses of alternative surface discharge and diffuser designs were completed (see Figure 12). These math models utilized different discharge configurations and were aimed at minimizing the number of tests that would be required in the physical model, thereby reducing the cost of the overall study.

Analytical Thermal Modeling

The Taiwan mathematical model in 1986 for thermal discharge was not the first such analytical model created at Alden. Analytical model studies had been conducted over a decade before. The first major analytical thermal model

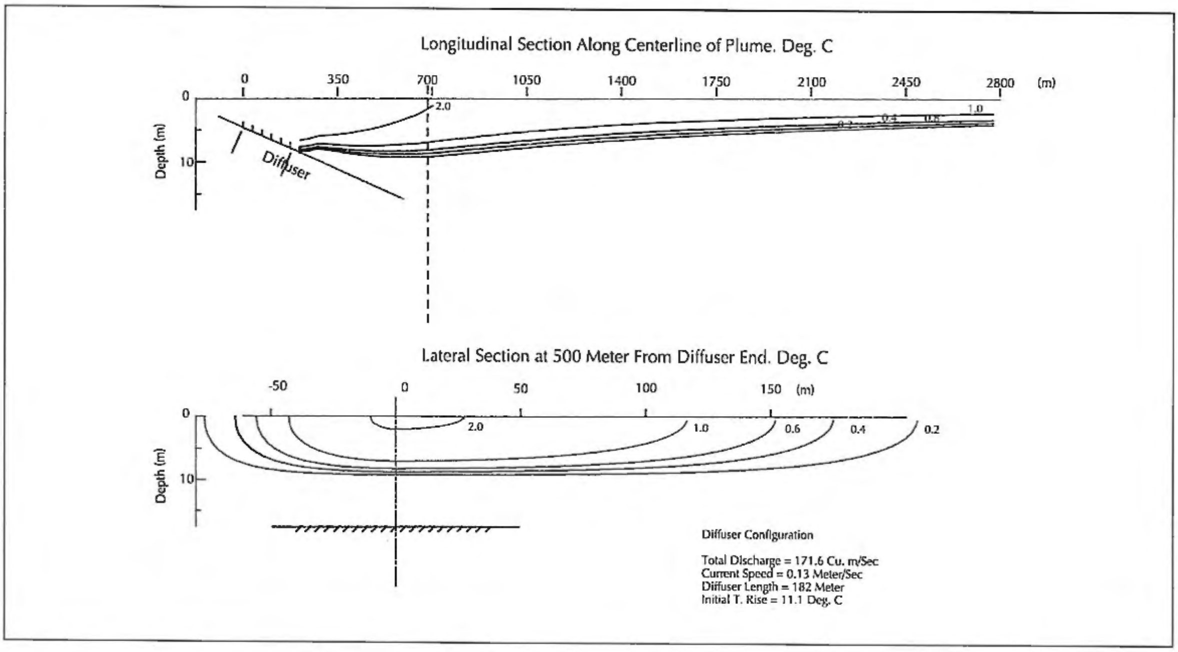

FIGURE 12. Cross-sectional isotherms from the proposed Taiwan diffuser.

study was started in 1974 for the Seabrook Station. Two types of analyses were conducted for Seabrook's thermal discharge to augment the physical hydraulic model study results. Near-field, buoyant jet diffuser analyses were used to quantify the effects of ambient vertical temperature and salinity concentrations on the plume dynamics and surface temperature rises. A second study, a far-field analysis, was used to predict the extent of the plume beyond the area covered by the physical model. The study utilized the equations of mass, momentum, thermal energy and salt in conjunction with various empirical expressions for drag, friction, entrainment, spread and surface heat transfer. The benefits of analytical modeling, which is now a standard practice at Alden and other consulting firms, are optimizing a design and determining which variables are most important. Then, the most favorable designs can be physically tested to confirm or further optimize performance.

Incidentally, the Seabrook Project led the way in having the largest number of studies performed at Alden. Thirty-one studies were recorded in the files related to Seabrook, and include analytical, waterhammer, backflushing, intake, sump, startup, thermal model, circulating water pump, diffuser, testimony, evalution, pipe and meter calibration. Part of Alden's versatility was embodied in this one project.

Soon after George E. Hecker became Director of Alden in 1975, one of Harleman's students at MIT, Dominique Brocard, came to Alden and eventually became the Assistant Director. During his stay at Alden, he used skills acquired from his mentor to conduct analytical modeling of thermal discharges. One of his first models, in 1978, was for the Mercer Generating Station on the Delaware River. A transient, one-dimensional model was used to account for the effects of the meteorology and tidal velocity fluctions in the Delaware River. An integral jet model that allowed the prediction of the three-dimensional temperature rise patterns produced by the heated plant discharge and modified to account for the effects of the opposite bank on confining the plume was superimposed to predict temperature rises in the river.

In the same year, a similar study was completed for a proposed power plant site in Charlestown, Rhode Island. The following year, a number of such models were studied analytically. The area in the East River around the Ravenswood Station in New York City was studied with another analytical model. Besides including the effect of this one station, the heat discharged by five other plants was taken into account. Two field surveys were made, and they showed favorable agreement with the mathematical model.

In the early days of analytical models, Alden did not always have the in-house computer capability to do the complete study. Being associated with WPI became a distinct advantage at these times since the school had large computers. Alden frequently leased time from WPI to utilize their computers.

In 1980, a simple advection/diffusion model was used to predict the background heat buildup from the Egyptian Ismalia Plant discharging in Bitter Lake. The study also included a 1:64 physical scale model used to predict the degree of recirculation that would be encountered in the field.

A combination of two, two-dimensional finite element codes were used in 1985 to predict the time-varying far-field temperature rises and the indirect recirculation produced by an enlarged power station at Castle Peak Station in Hong Kong. The study utilized two codes, developed by MIT — CAFE, which calculated the tidal circulation patterns (see Figure 13) and DISPER, which calculated the distribution of a tracer such as heat. Combinations of plant loads and a range of tidal conditions and prevailing winds were analyzed.

The same programs were used in 1987 to analyze the temperature effects of cooling water discharging into a section of Maine's Saco River from the York County Waste-to-Energy Plant. The plant discharged into a pool created by the Spring, Cataract, Bradbury and West Channel dams.

The last thermal mathematical model of Alden's first century was in 1992 for the Ao Phai Power Plant in Thailand. The study involved an investigation of three discharge schemes: surface channel, near-shore pipe discharge and off-shore submerged diffusers. The analysis was conducted in two portions to predict the plume isotherms in the near field and to predict the background temperature rises induced by the far-field phenomena of dispersion, tidal flushing and heat transfer to the atmosphere. Finite element methods to study the far-field and integral-type analysis (using Alden's SBJET program) were used for the near field.

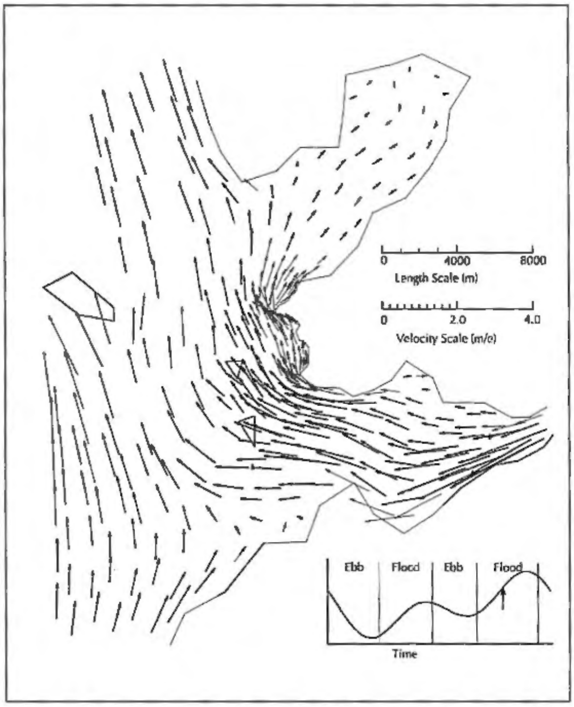

FIGURE 13. Numerical modeling of currents.

Computational fluid dynamics had reached the stage where thermal analysis using these techniques in simple near-field cases for discharges and ambient conditions was always possible. On the other hand, physical models are still required for more complex cases, such as plumes interacting with boundaries, or other plumes, reversing currents or the need for detailed thermal patterns. Costs of thermal studies with physical models can sometimes be minimized by using mathematical models to eliminate numerous schemes before testing begins or in conjunction with the testing of the physical model.

Hydroelectric Power Models: Overview

Alden has been involved with many aspects of hydraulic modeling for hydro stations since the 1920s. Models included spillways, plant alignment, intake and discharge flow patterns and gate studies. By the 1960s, most major U.S. hydro sites had been developed, and the utility companies shifted emphasis to large steam stations, and then the addition of pumped storage projects. With the latter exception, hydro power modeling diminished in the 1970s, until

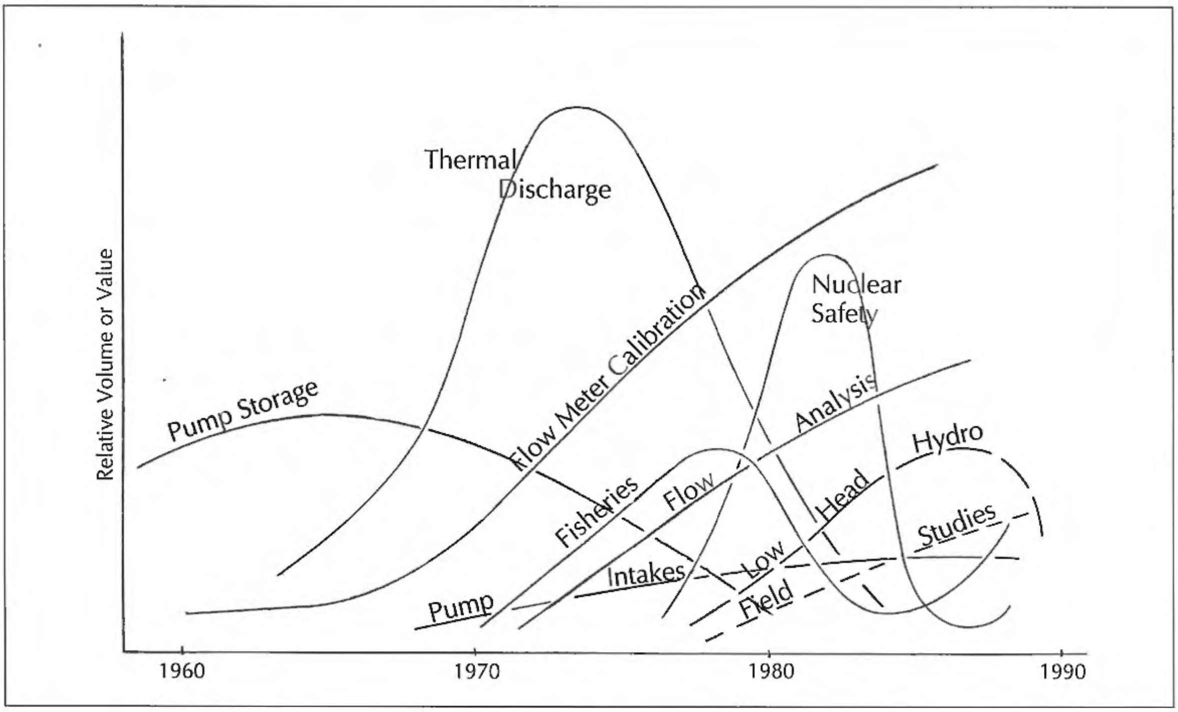

FIGURE 14. The variation of funded research at Alden.

the oil embargo and favorable legislation occurred. By the late 1970s and all through the 1980s and into the 1990s, hydro power modeling would again become a very substantial activity at Alden. The hydro modeling in the 1970s and 1980s would include new areas that had not previously been major areas of work—hydro models where navigation and sedimentation were major concerns.

As in so many other fluid-related areas, the work would come in "waves." Some of the waves would be sharp peaked and others much longer. On a relative scale, the various waves of work at Alden have included thermal modeling, which probably had the highest peak and longest base, and others such as pumped storage and field studies (see Figure 14).

Large, detailed intake models for hydro power stations became common in the 1970s because the total head at many sites was as low as 15 to 20 feet, and bulb or tube turbines were being proposed to minimize powerhouse excavation and cost. These units (not used in the United States until the late 1970s) were sensitive to approach velocity patterns and the turbine suppliers had strict requirements for approach flow distributions at the powerhouse intake. The re-emergence of hydro power would also favor Alden's traditional activity in field turbine testing. In 1970, hydro power accounted for 16.2 percent (64,000 megawatts) of the nation's generating capacity. By 1991, 10 percent of the nations's electric power came from hydro with its installed capacity reaching 92,000 megawatts.

Federal Law & Relicensing

When hydroelectric power was first conceived in the late nineteenth century, there were only a few federal or state laws regulating the construction of structures in streams and the industry itself. This policy was gradually changed through legislation that tried to preserve the public's interest in public lands as well as navigable rivers.

The Federal Water Power Act of 1901 applied to public lands, and the Act of 1906, as amended in 1910, applied to navigable rivers. The Act of 1901 limited the rights on public lands to mere revocable licenses. Licenses obtained under this act reflected the views of administrative officers and were subject to change at discretion. The license for power plants on navigable rivers, under the Act of 1910, required a special act of Congress in each instance and was limited to fifty years. Plans were subject to Federal authority, and locks or other navigable facilities might be required at the time of the original construction or at some later date. The acts contained no expression of policy nor did they specify what would happen to the projects at the end of fifty years. It is easy to see that these acts made it difficult to obtain financing to construct hydroelectric projects.

The legislation that changed the picture was the Federal Water Power Act of 1920. Under this act, which was a contract between the government and the licensee, an applicant could secure a license for up to fifty years. The license specifically spelled out the conditions that the licensee had to fulfill, and these could not be changed unless the licensee breached the contract. When the license expired, the government could take over the site for its own use, could permit the site to be taken over by others, or could issue another license to the original licensee.

If the properties were taken over by the government or by others before the license expired or at the termination of the license, a just compensation had to be paid to the licensee. This compensation, called a net return, was based on the licensee keeping good and accurate financial and technical records. If the site was not taken over by the government or others, the licensee was entitled to a new license on such terms as was reasonable in view of the conditions existing at the time of renewal.

When this Act of 1920 passed, it favored municipalities over private interests in issuing licenses. Regardless, it was so much better than the previous legislation that it promoted the financing and construction of many of the river hydroelectric plants. By 1922, 39 licenses had been issued under this act, for a total of 2,040,000 horsepower. In addition, the Federal Power Commission still had 309 applications for licenses. For the preceding 19 years, only 863,000 horsepower had been developed.

The 1920 Federal Water Power Act resulted in model work being performed at Alden related to dams, spillways and powerhouses starting in the early 1920s. However, more work was generated by 50-year relicensing than by the original act. The Federal Energy Regulatory Commission (FERC), which replaced the Federal Power Commission by the Department of Energy Organization Act of October 1977, listed from two to 18 projects each year from 1970 to 2001 up for relicensing (except for 1993 with 173 projects and 2000 and 2001, with 36 and 33 projects, respectively). From 2002 to 2033 16 projects per year are scheduled to come up for relicensing.

Besides the Act of 1920, other legislation affected the hydroelectric industry in the twentieth century. In 1978, the OPEC oil cartel was in control of the world's oil supply and caused fuel oil and gasoline shortages in the United States. Home heating oil cost rose over 40 percent within two years. As a result, Congress passed the five-part National Energy Act of 1978. One section of this act was the Public Utility Regulatory Policies Act of 1978 (PURPA), which was designed to reduce U.S. dependence on foreign oil and encourage the development of small power production facilites, particularly small hydro power. PURPA established the rules and regulations regarding the purchase and sale of electricity from small power producers and cogenerators. The act mandated that utilities must buy the power produced by small hydrogenerators at a rate not to exceed the cost to produce the power itself or purchase it from another (*i.e.*, the avoided cost). In essence, utilities had to buy high-cost power from these small, relatively expensive (because of their small size) units. In the 1990s, these contracts would cause financial difficulty for some utilities because competitors could supply cheaper power. Also, the utilities themselves were generating less expensive power because of over capacity, but the contracts had to be honored or "bought out."

As a further tax incentive to encourage small power development, Congress passed the Crude Oil Windfall Profit Tax Act in 1980 (COWPTA), which was modified in 1981 and 1982 by the Economic Recovery Tax Act and the Tax Equity and Fiscal Responsibility Act. Significant tax benefits became available to public and private developers. Lastly, PURPA allowed the FERC to exempt small hydro facilities from most federal and state utility regulations for facilities up to 30 megawatts.

Many projects that qualified under PURPA were very small, had limited funding and were not as tightly regulated as larger hydro projects.

As the result, they usually refurbished old existing sites and did not require the services of Alden. Other projects, which required special optimization or interacted with navigation facilities, were model tested and became a major source of new work for Alden. As a direct result of the legislation and the greater cost of fuel, the "gold rush" for low-head hydro began. There was voracious competition to get FERC licenses at existing dam sites. Many of the small sites (from 5 to 10 megawatts) that had operated from the 1920s to the 1960s, but had been abandoned in favor of big steam units, suddenly had value to utilities. Numerous old stations were brought back on line. Many stations had their capacities increased because of the greater value of the site and the water being spilled. An industry for low-head, mini-head and micro-hydro plants developed, with many major engineering firms and new small ones getting into the field.

When hydro project licensees neared license renewal time, they inquired about some of the ambiguous parts of the Act of 1920. To clarify this act, Congress passed the Electric Consumers Protection Act of 1986 (ECPA). Congress clearly gave the FERC the authority to regulate the hydroelectric industry. Under the ECPA, the FERC has the ability to revoke licenses for violations of the act or to impose fines up to $10,000 per day per violation.

The ECPA requires existing licensees to notify the FERC at least five years in advance of the license expiration date on existing licenses for which relicensing will be sought. The ECPA also requires those applying for relicensing to make any technical information they may have available to competitors for the site. In spite of this, the relicensee is favored by the act. Also, contrary to the 1920 Act, municipalities are not favored by the ECPA.

Environmental Considerations & Hydropower

If the early environmentalists were happy about the fifty-year license limitations they sought under the 1920 Act, they had to be ecstatic by the provisions of the ECPA. Relicensing required the FERC to consider state recreational planning as outlined in the Statewide Comprehensive Outdoor Recreation Plan (SCORP) required under the Land and Water Conservation Fund Act. In addition, recommendations made by the National Marine Fisheries Service, the U.S. Fish and Wildlife Service and the state's fish and wildlife agency had to be factored into the FERC's decision-making process. To illustrate the complications, the U.S. Fish and Wildlife Service has to take into account the Endangered Species Act, the Fish and Wildlife Coordination Act, the National Environmental Policy Act and the Clean Water Act of 1972 when making their recommendations to the FERC. Even the recommendations of Native American tribes have to be factored into the FERC's decision.

Under licensing or relicensing, the FERC is required to investigate whether the sites are being, or will be, efficiently utilized and properly managed. Utilization may require changes in the geometry of the structures or the site, or may necessitate updates or changes to the powerhouse turbines. Alden did a number of studies from the late 1970s to 1994 that involved such modifications.

Hydro Studies

One of the early (1980) hydro intake models during this period was for a small hydro project proposed in Lawrence, Massachusetts. A company wanted to develop the power potential at the existing Essex Dam on the Merrimack River. Optimizing inlet flow conditions and maximizing net head were the priorities.

From 1981 to 1987, Alden conducted four studies relating to modifications to existing low-head hydroelectric projects. The first project (located in Brunswick, Maine) was an intake structure to two tube turbines being used to reduce the spillage over the flashboards on the dam during periods of high flow. The intake had a square penstock with two elbows in the same plane, with the second elbow ending in a transition from square to round. Proper flow conditions were obtained at the turbine entrances and were verified in the model using velocity traverses at the model turbine inlet and a swirl meter at the turbine location.

The second project was for the Worumbo Hydroelectric Project located in Lisbon, Maine. This model study was conducted in two phases. The first phase called for a study of a proposed powerhouse with three tubular turbines, having a total flow capacity of 7,500 cubic feet per second (cfs), to replace an existing plant having a total flow of 900 cfs. The model results indicated that the canal and headgate structure had to be modified and the bottom of the head pond had to be excavated to accommodate the substantial flow increase. In the second phase, the powerhouse location replaced a portion of an existing dam. During this study, rating tests were conducted for the spillway, and various headrace evacuation schemes were evaluated.

The Lockwood Hydroelectric Project on the Kennebec River at Waterville, Maine, was studied to investigate flow patterns at the intake and head loss from the head pond to the tailrace. The six old units in the existing plant were to be overhauled and a new unit, with twice the flow of each existing units, was proposed for construction next to the plant.

Finally, the fourth project was the Lewiston Falls Hydro Project on the Androscoggin River in Maine. This study of a new plant involved the evaluation of flow patterns approaching the intake and losses in the approach channel. Cofferdams used to keep water out of the project during construction were also evaluated for various flow conditions.

Another low-head project involved replacing five turbines with a total flow of 1,100 cfs with three units having a total flow of 2,130 cfs. The proposed units (near Paterson, New Jersey) would occupy three of the five existing intakes. Besides studying the intake flow patterns, the model was used to evaluate the head losses. Intake flow patterns are very critical in all low-head hydroelectric power plants; improper approach flow conditions can be the source of a high percentage of the head loss through the structure. Poor flow patterns outside the structure can also be the cause of reduced turbine performance.

For the Emporia Hydroelectric Projects on the Meherrin River in Virginia, a vertical shaft Kaplan turbine was proposed to replace a wet pit turbine. The model evaluated the modifications to the existing structure and measured velocity distribution and swirl immediately upstream of a vaned elbow leading to the turbine. During the study, vortex activity was observed in the forebay and was eliminated using vortex-suppression devices.

In 1986, a model study for the new Hydro Kennebec Station in Winslow, Maine, focused on inlet flow patterns for the turbines, crest gate performance, flow conditions in the tailrace and other related issues. The pit turbines had a flow capacity of 4,000 cfs at a head of 27 feet.

One power company proposed to abandon ten units, with a total capacity of 8,000 cfs, and replace them with two pit turbines with a capacity of 15,200 cfs at the Swan Falls Project on the Snake River in Idaho. The new powerhouse would be built on the east side of the river where the existing bypass sluiceway was located. The model showed a large flow along the face of the ten abandoned units toward the new powerhouse, causing poor flow patterns at the entrance to the new units. Guide walls were used to remedy the problem. In addition to this problem, the model showed that the excavation planned in front of the new powerhouse was excessive and could be minimized without affecting the turbine performance. This factor alone saved the utility more than the cost of the model.

Sometimes model studies conducted for the same client and on the same river were performed simultaneously, which was the case for the Crescent and Vischer Ferry Hydroelectric Projects on the Mohawk River near Schenectady, New York. Both powerhouses underwent structural renovations and the study was conducted to evaluate the entrance to the turbine to determine if better flow patterns could be achieved. The Vischer Ferry study also included the development of a new flow-regulating structure to bypass flow by the powerhouse when necessary and the development of an ice boom.

Navigation Models

Some utilities were increasing their electrical production capabilities utilizing features of the 1920 Act that were not previously used. American Electric Power Corporation was the first private utility company to build a hydro power project at a federal lock and dam facility. In 1978, Alden evaluated intake velocities and the navigational impact of building a hydro power project on an Army Corps of Engineers (COE)

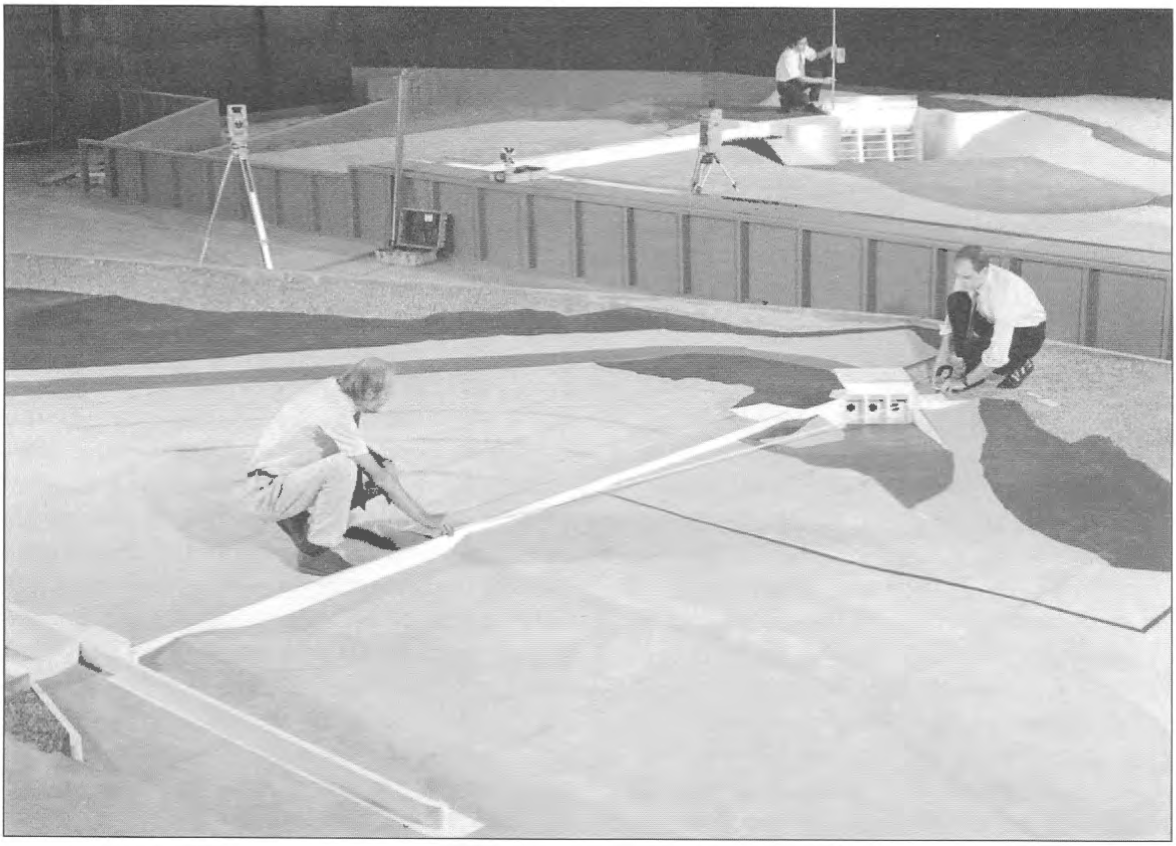

FIGURE 15. Overall navigation model (foreground) with separate detailed powerhouse model (background) for the Demopolis Project.

operated lock and dam on the Ohio River, 40 miles downstream of Parkersburg, West Virginia. The run-of-the-river power plant was to be situated on the right bank of the river and would be called Racine. In general, these types of studies required two or three models to address issues raised by the COE and turbine suppliers. A detailed large-scale intake model was used to evaluate velocity distributions. A second overall model (typically 1:100 to 1:150 linear scale) was used to evaluate currents and surges that could affect navigation. In some cases, a third distorted scale model addressed sedimentation.

The overall type of model became known as a navigation model. Three other navigation models, Demopolis (see Figure 15) on the Tombigbee River in Alabama, and Lock and Dam Nos. 13 and 9 on the Arkansas River in Arkansas, were tested at Alden in later years. Because of the large size of these models, technical considerations and experience dealing with the COE, Alden was one of only two or three laboratories in this country interested in doing this type of work.

Since Racine was the first such private project on a COE site, the COE had no written specifications or formulated review procedures at that time. As the result, positive interaction between Alden, COE and the project owner was necessary to see the project through. The 1:150 model showed that the power plant discharge proposed in the original design created a large eddy at the lower lock approach during low river flow conditions. This eddy impeded barge traffic into the lock. A relatively small excavation in the tailrace that confined the plant discharge to the adjacent river bank remedied the problem. Other navigational concerns were studied by using time-lapse photography of a model non-powered barge train coasting into the lock and by running the model with and without the power plant in operation. Later models would have a scaled motorized tug and barge.

In the Racine navigation model, velocities were measured using floats with candles and a rotating segmented plate in front of an overhead camera. The same method had been developed 30 or more years earlier (see Figure 16). Reduction of these data is time consuming and requires a photographer. When it was realized that more of this work would be coming, Alden developed a computerized float-tracking system. This method allowed flow patterns to be determined from video recordings and plotted using computer-aided design (CAD) software. The output was velocity vectors that were then superimposed on project drawings.

All concerns of the COE were addressed, and Racine was built. It is currently producing power and has not encountered any difficulties. The major general requirements of the COE included:

- no increase in upstream flood levels;
- no impact on lockage cycle time; and,
- no impact on dredging.

By the time the Demopolis Hydro Project model study was commissioned in 1983, the COE had written specifications relating to model studies. The concerns on the Demopolis site related to the modifications of river currents and surges imposed by the power plant discharge. Very long excavated intake and discharge channels were needed for this proposed plant. The model showed local downstream cross-currents from the hydro plant discharge in the lower lock approach area where the push tows would cut power and subsequently lose maneuverability. The problem was remedied by selective discharge channel excavation in the "Selma chalk," which comprised the river bank flood plain, and directing the plant discharge flow toward the bank opposite the navigation lock. A second, larger model of only the power plant intake area was built to study the flow patterns at the entrance to the turbines. Flow patterns approaching this area were obtained from the overall model and imposed at the inlet to the powerhouse model. Towards the end of the study, basic COE approval had been secured for the construction of the project, but, unfortunately, the project ran into financial difficulties and was canceled.

In 1984, a detailed powerhouse and an overall navigation model was commissioned for a

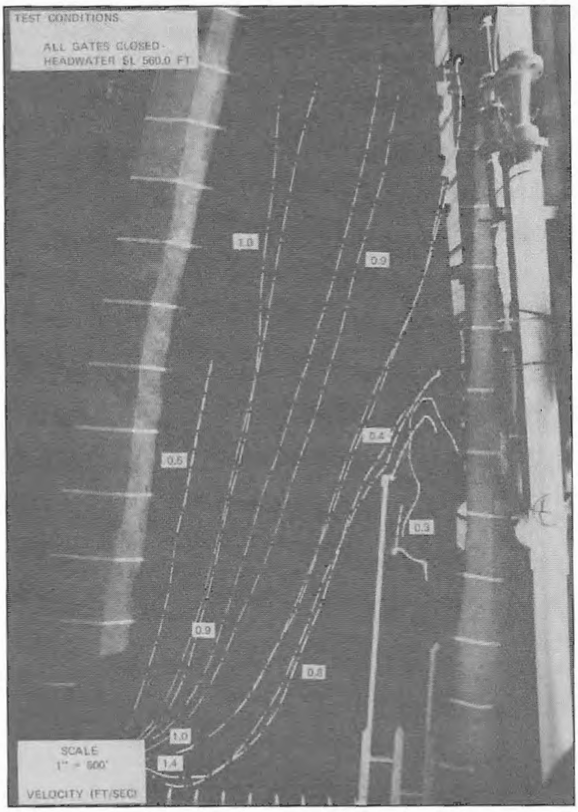

FIGURE 16. Streak lines and velocities in a navigational model.

proposed 33-megawatt hydropower station to be located at Lock and Dam No. 13 on the Arkansas River near Fort Smith, Arkansas. The results from the model studies showed acceptable flow conditions at the lower lock approach and minimized head losses through the powerhouse. The tailrace configuration was also improved through the use of the model, effectively widening the river downstream of the dam and permitting a more unrestrictive passage of flood flows. Despite the encroachment of the overflow embankment by the powerhouse, the tailrace allowed project flood flows to be passed without increasing the upstream water elevations. Proper lock performance with the added powerhouse was verified through the use of a COE remote-controlled scale model of a barge tow entering the lock both upstream and downstream. The tow model indicated forces acting on the tow with and without the power plant in operation.

For this navigation model, a new construction method was developed and utilized. Contour maps of the prototype were digitized using a linear resistance gauge for position and a manual entry key pad for elevation. These data were stored in a computer and used to print out a continuous sheet of the model elevations versus model position along a transect in the model. This sheet was then pasted on a thin aluminum film and cut along the elevation line using a bandsaw. A rotating laser leveling beam was used to install the templates using spot levels printed by the computer on the template paper.

Sediment Transport Modeling

Because the Arkansas River transports a tremendous amount of sediment during flood stages and is highly developed from a navigation standpoint, the COE required that the proposed hydro plant's impact on river morphology be studied with a movable bed model. A separate model for Lock and Dam No. 13 was constructed for this purpose. The model was operated in the transient mode simulating a few years of typical river flows. Because of the COE's experience in this type of modeling, it required Alden to use coal as the movable material in the model, and the coal had to be crushed and graded relative to size and density.

The movable bed transport models required innovation in many aspects of modeling in order to quickly construct, operate, calibrate and provide a model that met the COE's requirements while producing reproducible model data. The first challenge was obtaining a stockpile of clean coal having the required density and gradation. Various suppliers were investigated, and handling techniques were developed. Aluminum templates were built and placed in their proper positions in the model. The model was then filled by hand with coal to the correct elevation on the templates and the templates were gently removed to prevent movement of the coal. The model was also equipped so that it could be stopped at any time in the flow cycle and be drained from the bottom to prevent the coal from moving during this process. The procedure was reversed for restarting. The difference in the transport of bed material around the site both with and without a power plant in place was determined. Of special importance was the required maintenance dredging in the entrance areas of the lock.

The Lock and Dam No. 13 model also used a computerized system, developed on some of the earlier large tidal models, that allowed automatic regulation of inflow, outflow, spillway gates and powerhouse flow. Such automation of data was especially important in the repeatability of the hydrograph for all the different series of tests. These systems became so developed that the model could operate around the clock with little or no continuous staffing, allowing a much quicker turnaround for evaluating the numerous tests required by the COE.

A technique to reduce hydrographic data was also developed for this model. At different times in the river flow cycle and at the end of the cycle it was necessary to obtain the river contours. In the past, an engineer used a level and rod to obtain contours. In a model of this size, this method would take two or three men many days to survey and get accurate results. Level I beams with a traveling platform incorporating an x-y position system were used to locate an elevation rod at the point of interest. An operator moved the rod tip to the coal bed and pressed a button to record the position and elevation in the computer. A few hours after completing the survey, the operator could see the contour map of the river bottom.

After construction permits were issued, building of the powerhouse at Lock and Dam No. 13 was started while the model study was still ongoing. It was decided that the position of the plant had been fixed by the model study and that further changes developed from the study would be only in the plant approach or discharge areas. In fact, the dedication of the plant took place before the final model test, to verify some previous data, had been completed at Alden.

In 1988, Alden performed similar studies for a proposed 42-megawatt hydro station at Lock and Dam No. 9, located on the Arkansas River near Morrilton, Arkansas. The study was also to include a navigation model, a movable bed model and an intake model. Rather than having three distinct models, as had been the case for Lock and Dam No. 13, it was decided to construct the movable bed model in the same area as the navigation model. Keep in mind that the

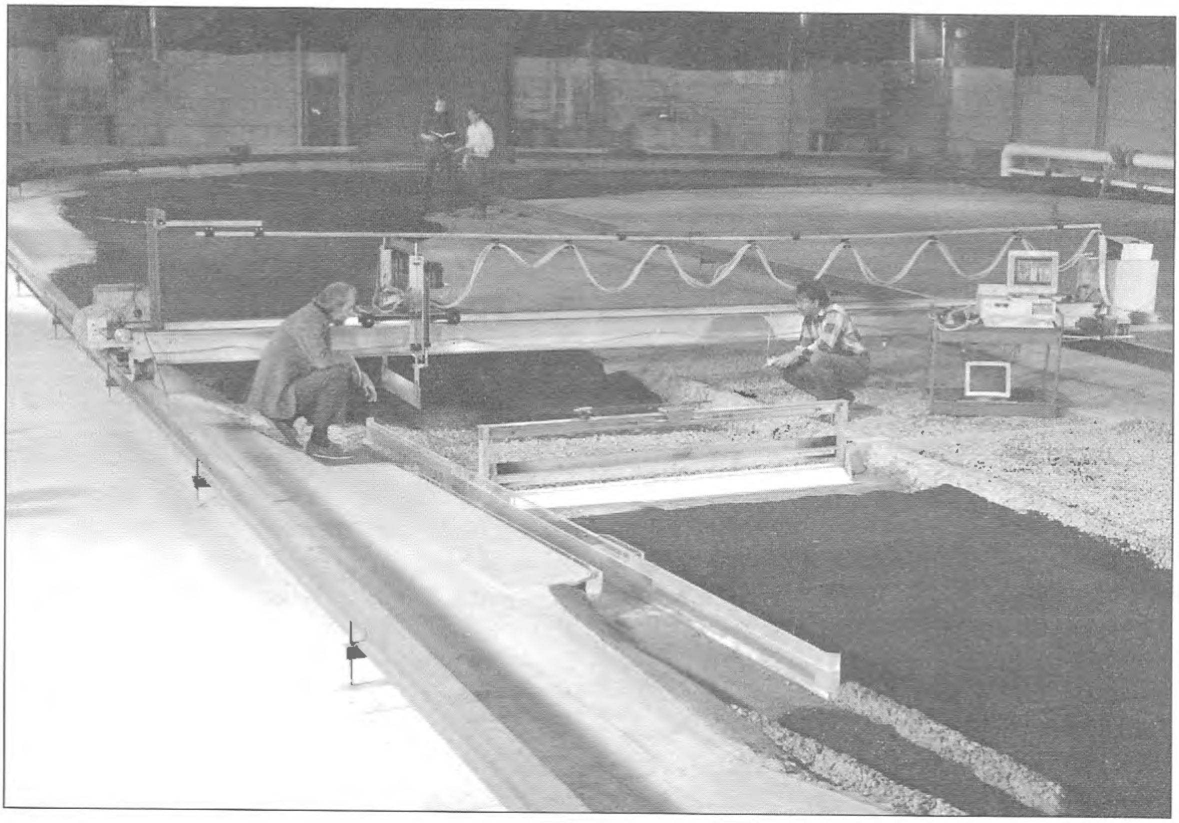

FIGURE 17. Computer-controlled screeding device for moveable bed model.

navigation model was constructed to facilitate removal of those model parts that would not be common to both models. To be cost effective, this method required that all navigation model studies be completed before starting the movable bed studies. If successful, the method would save space as well as construction time.

To reduce the labor in preparing the movable bed, another Alden innovation was developed. The reproduction of the river bed topography in the earlier Lock and Dam No. 13 model had been labor intensive and time consuming. A computer-driven screeding system to accurately form the river bottom was designed based on the same type of platform used to gather the river topography information in the Lock and Dam No. 13 model. The platform contained a stepper motor driving the screeding apparatus through a chain drive. The screeding apparatus was a flat blade with each end operated by chain driven stepper motors (see Figure 17). The system was operated by a personal computer containing the topographic information and utilizing x-y-z coordinate feedback from the platform. Manual labor was only necessary to maintain a small excess amount of coal in front of the flat blade. This device was a tremendous success and demonstrated its reliability and advantages over the hand molding of the river bed by repeatedly and accurately forming the river bed for the many diverse studies conducted in the movable bed. There certainly was no lack of praise for the system, especially from those who had shoveled and placed the coal in the Lock and Dam No. 13 model.

Sediment transport models, or the so-called movable bed models, were not new to Alden. The first such model tests were conducted in 1957 for the Elrama and Dickerson projects. Tracer studies, where movable material indicates movement tendency, were done much earlier. The materials used to simulate the movable bed varied depending on the fall velocity and the specific gravity of the prototype material, the model scale ratio, field data on erosion patterns and calibration tests.

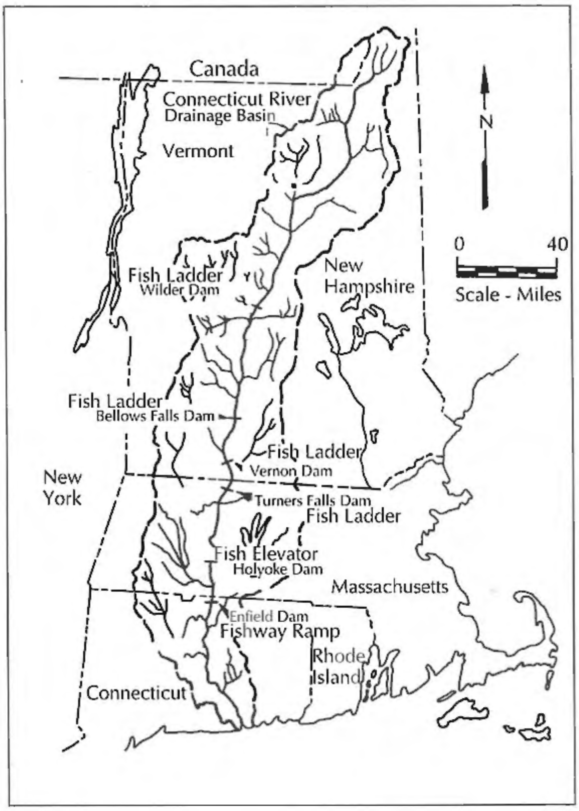

FIGURE 18. Connecticut River drainage area.

Relicensing & Fish Passage

Perhaps the most difficult parts of licensing or relicensing hydroelectric power plants since the passage of the ECPA of 1986 have been recreational and environmental issues, especially as they related to fish, wildlife and botanical resources. Before this act, the utility put up a dam, spillway and powerhouse, and began producing power. After the ECPA, these same structures, which were impediments to fish, became a source of frustration to the owners or potential owners who tried to foresee the FERC's demands on environmental issues. Utilities were perfectly at ease with the technical nature of power production, but few had the necessary staff to study and recommend changes or additions to existing facilities to satisfy the FERC's environmental requirements. Utilities had a choice of staffing or hiring outside consultants to satisfy the ECPA. Both paths were followed, and Alden worked with both utilities and consultants on fishways, fish screens and fish behavior.

With the building of numerous dams in the 1800s and 1900s, people had become increasing concerned about the cessation of fish migration, and limited studies on fishways for upstream passage were begun. Many early dam builders had made some effort to provide upstream passage. By the 1940s, successful passage of shad had been demonstrated at the Bonneville Dam on the Columbia River in Washington state, which prompted regulatory and other personnel to investigate shad fishways for other rivers in the United States.

One river that benefited from Alden's studies was the Connecticut River (see Figure 18). From the time that the Holyoke Dam was built to supply water to mills, shad and Atlantic salmon were prevented from accessing their spawning grounds in the upper reaches of the river. Shad had at one time gone as far as Bellows Falls, but by 1849, they could go no farther than Holyoke. Salmon, on the other hand, had spawned as far as Beecher Falls, Vermont, on the Canadian border. By 1798, they were limited to only as far north as Turners Falls. Sixteen years later, the salmon spawning migration had ceased.

Starting in the early 1950s, with a study for the Holyoke fish elevator, Alden has been involved in developing fish ladders or other passage facilities for four other dams on the Connecticut River, finally opening up the entire river to the spawning fish. In 1955, the first year of operation, the Holyoke elevator passed a disappointing number of shad, only 4,899. Today, it is not rare to see over a half million shad pass this elevator, mostly in the month of May.

Successful fish ladders need to satisfy a number of criteria. First, the fish have to find the entrance way, which requires attraction water that is fast enough to be sensed by the fish but not so strong that the fish cannot swim against its current. If the attraction water is from a different source than ladder water, the melding of the two waters near the entrance needs to be smooth, with a velocity distribution as uniform as possible across the cross section. To achieve this, a floor diffuser is used where internal hydraulics must be optimized. The gradient down the ladder cannot be too large, nor can the velocity be too high to prevent the fish from going from one pool to the next. Also, at every pool or drop in the ladder, there has to be a relatively calm area where the fish can rest, if necessary, and not be carried down the ladder.

Hydraulic models are useful in the design of fish facilities because detailed velocity distributions and overall flow patterns can be measured at critical locations and evaluated. Based on previous experience, the internal hydraulics, entrances, weirs or other components can be quickly optimized.

Fish ladder types also depend on the species of fish. West Coast ladders for salmon consist of a series of pools created by small weirs. The salmon go up the ladder by jumping over each weir into the next pool. In the Connecticut River, the predominant fish is shad, normally a non-jumper. The fish ladders in this case are usually of the vertically slotted type.

In 1973, approximately 20 years after the effort at Holyoke, Alden studied the Turners Falls fish passage, the first dam upstream of Holyoke. The fishway was designed to handle 40,000 Atlantic salmon and 850,000 shad. At this location, fish have two ways to get over the dam. At the upstream part of the dam, there is a gatehouse that controls water to a long power canal. The Cabot Station is at the far end of the canal and discharges into the Connecticut River. Fish have an option of using a 66-pool ladder at the Cabot Station or a 42-pool ladder at the spillway. All fish, whether they went up the Cabot Station or the spillway ladder, pass through the gatehouse fishway, which contains viewing, counting and diverting areas. Fish can be captured at this location for study or transport to other areas. With the 1973 Turners Falls model study, Alden began a series of model studies on fish passage that continued to the present, and will continue in the future as long as there are fish-related relicensing issues.

The Turners Fall fish passage model was used to investigate the location of the fishway entrance relative to the dam and flow coming from the overflow gates. The model contained a portion of the dam, two bascule gates and a portion of the downstream channel topography. The topography was extremely rough, and locating the fishway entrance was challenging to say the least, since fish need to sense the attraction water in order to find the ladder. The gatehouse slotted fishway was also evaluated and optimized. In 1986, the gatehouse ladder entrance and a portion of the Cabot Canal were studied when increased flows in the canal were being considered. The Cabot Station and spillway ladder consisted of a series of pools, each 1 foot above the other, separated by baffles having open ports such that the fish could swim over the baffle or through the port to reach the next pool. Finally, in 1991, due to fish mortality in the Cabot Station log sluice fish sampler, Alden was asked to look at different geometries for the opening in the sluice bulkhead gate slot, the inclination and the length of the sampling screens, the arrangement of the lateral guide walls and the screen porosity.

Alden studied the fish ladders for the next three upstream fish ladders on the Connecticut River. The first study was for the Vernon Dam, located between Vernon, Vermont, and Hinsdale, New Hampshire. The fish ladder was located on the west bank of the river, adjacent to the powerhouse. The studies of the slot type ladder, containing 25 pools, included the measurements of the pool flow patterns, the head drop between pools, the slot velocity distribution and the pool power dissipation.

Downstream Fish Migration

Although it was important to get fish upstream, regulatory agencies also became concerned with the plight of fish going downstream, either through the turbine or over the spillway. There had been wide ranging estimates of high fish mortality due to turbines. Some experience indicated that mortality through the slowly turning hydroturbines varied with the species, type of machine and head. With Kaplan and bulb turbines, the mortality of some species can be as low as about 5 to 10 percent. Depending on site specifics, Francis turbines may produce higher mortalities.

Downstream fish migration methods needed to be investigated and, in 1991 as part of a proposed capacity increase, a downstream fish migration scheme for Vernon Dam was studied at Alden. Based on velocity data, it was determined that modification of an existing trash boom with a vertical 15-foot skirt would be effective in directing fish to a trash sluice. When the plant expansion did not take place, an overall model was used to evaluate flow patterns approaching a fish pipe that would take downstream migrants around the hydro station. A detailed model of the fish pipe was used to evaluate internal hydraulics.

The fish ladder at Bellows Falls, located between Rockland, Vermont, and North Walpole, New Hampshire, was studied in 1980. Three different methods of supplying attraction water were studied:

- water from an existing sluice;
- a diversion conduit attached to a proposed tube turbine draft tube; and,
- a closed conduit from the head pond.

The downstream migration studies at Bellows Falls were started in 1989. The method to guide the fish was similar to the Vernon Dam study in that it used a boom with a 15-foot skirt to guide fish to an existing ice and trash sluice in the Bellows Falls power canal. Two alternate schemes were also studied. One called for a bypass at the southeast corner of the forebay, and the other bypassed along the powerhouse face to the west end of each trashrack bay.

The fish ladder studies for the Wilder Station, located between Hartford, Vermont, and Lebanon, New Hampshire, commenced in 1982. The study included a portion of the main entrance weir collection channel and the attraction water diffuser, including the first two pools. An investigation was also made relative to the supply of the attraction water. This water would be supplied by a proposed turbine to be installed in an empty south bay of the powerhouse.

A downstream fish migration scheme consisting of a floating boom with a 10-foot skirt leading to a bascule gate was investigated for the Holyoke site. This study also evaluated the partial removal of a submerged dam to determine its effect on velcoitiy patterns and downstream migration.

Fish Passage in the Susquehanna River Basin

The predominant fish on another river, the Susquehanna River in Pennsylvania, is also shad, and four dams block their passage to 300 miles of their spawning grounds. By agreement between the four utilities owning the dams and the supervising governmental agencies, all four dams were to have fish passage facilities by the year 2000, thus allowing shad, river herring and other migratory fish access to the upper reaches of the river.

Fish passage model studies have been conducted at Alden for three dam sites on the Susquehanna River: Conowingo, Holtwood and Safe Harbor. A proposal for a study at the fourth dam site, York Haven, has been submitted and is currently awaiting approval. (Some of these dams were modeled approximately 70 years earlier by Alden.)

All three proposed upstream fish passage facilities for the Susquehanna River were fish elevators. When the Alden studies began, only one small lift facility was operating. This lift had been in operation since 1972, and was located on the west bank at the Conowingo Dam. Two Alden studies investigated east bank fishway entrance schemes at this site. The first study looked at a two-entrance concept. The concept for the second study involved three fish entrances, two floor diffusers and an energy dissipater in the flip bucket of the spillway gates used to supply water to the elevator. Part of the study involved minimizing air entrainment. For all three entrances, the velocity distribution was measured and adjusted to meet the requirements of fish biologists monitoring the tests.

At Holtwood, two fish elevators were studied. One elevator was located at the powerhouse and had two tailrace entrances. The other elevator, located at the spillway, had a single entrance.

For the Safe Harbor Dam, a number of models were tested in order to provide acceptable velocity distributions in the tailrace near the entrances. Another model was used to develop favorable internal flow hydraulics leading from the entrance to the fish elevator hopper, including three attraction water diffusers.

An interesting aspect of shad "tagging" was initiated by the Pennsylvania Fish Commission in 1985. The otolith, or earstone, of the shad grows a ring a day, similar to the rings on trees. It was found that when shad fry were immersed in a solution of tetracycline, the growth ring for that day absorbed the tetracycline. Using ultraviolet light and viewing the otolith under a fluorescent microscope, the tetracycline produced a yellow glow. By immersing the shad fry on different days, they could form a code to identify the shad's origin. The commission has been doing this at their Van Dyke Hatchery for all shad since 1985.

Collection Systems, Barriers & Diversion

In additional to fish passage by means of fish ladders or elevators at hydro plants and other dams, there are fish protection requirements for all types of projects located on salt or fresh water sites. Protection systems can be classified into four categories: behavioral barriers, physical barriers, collection systems and diversion systems.

One of Alden's first fish protection studies was performed in the early 1960s. The model was approximately 80 feet long by 35 feet wide. The model river water entered the model at one end and was regulated by a gate at the downstream end. The intake structure being studied was located between the two ends of the model. For some unknown reason, at some point in the study the client decided to see if fish would be attracted to the intake structure. The Alden Director at the time, Professor Hooper, tried to convince him that you could not model fish, and that most certainly with a fixed-end model, the fish behavior in the model would not represent its actions in the prototype. Nevertheless, the client insisted in going ahead with the fish test. A staging was erected in the rafters to quietly observe the fish behavior. At the appointed time, 500 small fish were trucked to the model and released. They all immediately moved to the upstream end and proceeded to dine on the incoming food that must have been in the water. For hours, the technician laid on his stomach on the staging, recording that nary a fish had left the group at the model inlet. The results were probably reported as inconclusive.

In contrast to this early study, Alden has been involved in numerous successful fish-related studies, starting with the Easton hydraulic fish screen in 1968, up to the current Eicher screen study. Alden's facilities and flexibility enabled many varied studies to be performed (see Figure 19). It is necessary to perform full-scale tests with various species of live fish under controlled conditions because fish behavior cannot be predicted. When basic technology is being developed using a variety of species, full-scale tests in the field are not appropriate. Site-specific studies, however, are now successfully done. With the environmental concerns that developed in the 1960s and 1970s, the power industry became interested in all aspects of fish barriers and handling.

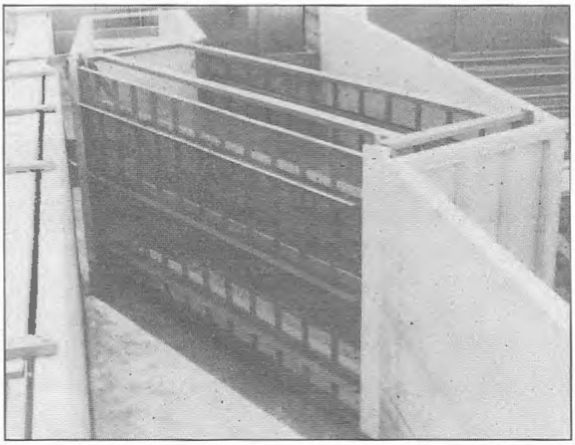

FIGURE 19. Angled screens and fish bypass in an outside basin.

The first study that used live fish was started in 1973 for the Nine Mile Point Nuclear Plant, Unit 2. Located on Lake Ontario, Unit 1 has a cooling water circulating system with an offshore intake and a near-shore discharge. For Unit 2, a Water Quality Certification required biological (fish) studies. With the possible exception of salmon studies in the Pacific Northwest, it is believed that this was the first large-scale systematic effort by a utility to investigate barriers, handling and diversion of fish away from an intake. The purpose of the initial study was to investigate fish behavior related to different aspects of the project. Hydraulic and biologic (fish) studies were conducted to investigate the performance of full-scale devices that would be incorporated into the intake. In some cases, a scale model was first tested to evaluate head losses with the proposed device. At the same time, for the most promising devices, a section would be evaluated at full scale with fish. Louvers, chains, baffle screens, as well as other devices were tested using alewife and smelt. Entrapment problems had occurred previously with these species. (These extensive studies continued until 1977.)

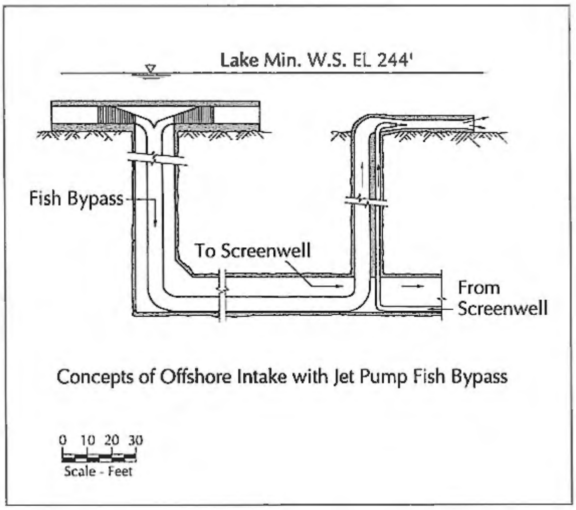

FIGURE 20. Concept of an off-shore intake with peripheral jet pump fish bypass for the Nine Mile Point studies.

At first, a holding facility had to be built. Since control fish would be used in each experiment, duplicate systems were required. It was decided to use 190-gallon galvanized oval horse troughs and 500-gallon round plastic swimming pools. The troughs were coated with a non-toxic epoxy paint, and each tank was piped with copper pipe to a sand filter to remove any large particles. Aquarium air pumps bubbled air through a stone discharge to supply oxygen to the fish. The first large group of fish arrived at Alden on a Friday afternoon and the fish were placed in the holding tanks. The next morning, the technician who arrived to feed and check the fish found them in a peculiar position, belly up. Investigation revealed that they had been poisoned by the various elements in the metal piping. The systems were immediately re-piped using only non-toxic plastic piping. The next batch of fish fared better, but after a while the multitude of fish in each tank began to kill themselves due to their own wastes. Including a biological filter in the system solved that problem. However, there was still some unexplained mortality. Finally, it was determined that fish need some current to swim against. The discharge water from the filters was then directed tangential to the side of the tanks, causing a rotating motion in the tanks — with the higher velocity water near the edge of the tank and nearly still water at the center. The fish were now happy exercising in their physically and biologically clean water.

Fresh and salt water fish were used in different studies. These fish were trucked to Alden from different sources. Once on the site, the biologists were responsible for an accounting of all fish. The freshwater pools were readily converted to saltwater pools by using a granulated aquarium product mixed with water.

Fish Transporting

Fish entering the offshore vertical intake pipe at the Nine Mile Point Station would be subjected to sudden pressure changes (see Figure 20). To study fish behavior under these conditions, a 1-foot square tank with a viewing window was constructed. The tank was filled three-quarters full of water, and fish were introduced into the tank. The alewife, smelt or coho salmon were allowed to become acclimated before the pressure inside the tank was quickly increased from 0 to 36 pounds per square inch (psi), to simulate their decent into the intake tunnel. They were held at 36 psi for 15 minutes, simulating the horizontal passage in the intake tunnel. Finally, the 36 psi pressure was released in a 2-minute period. When initially subjected to the 36 psi, the fish's air bladder was compressed, causing the fish to become disoriented and swim with their tails lower than their heads. They quickly recovered, however, and then swam normally. When the pressure was released, no ill effects were observed. After each test, the test fish were returned to a holding tank and observed for a few days. Comparison of these fish with control fish indicated no difference in mortality between the two samples.

Pumping is one method to transport diverted fish. Two methods to accomplish this were investigated. In the first method, a special mechanical pump designed to pump fish was acquired from Chile. This pump was a centrifugal pump with few vanes and a low rotation speed. Tests showed satisfactory results, but the feeling was that another type of pump — a jet pump — would be more advantageous. A literature search was conducted on core and peripheral type jet pumps, after which physical models of each were constructed and tested (see Figure 21). Although the peripheral jet pump required more input energy than the core jet pump to induce a given suction flow, the peripheral jet pump had better fish pumping characteristics. Jet pumping tests of smelts and coho salmon showed no noticeable undue stress on these fish. Alewive fish, on the other hand, displayed some fragile tendencies during the same testing.

As a further study on the jet pump, fish were introduced directly into the shear zone of the jet pump. Since the alewives had been shown to be the most fragile, they were used in these tests. Velocities in the shear zone were varied, and the fish were introduced first all head first and then all tail first. Careful inspection of all parts of each fish were made in addition to observing their behavior in the holding tanks after the tests.

Another part of the collection system was the piping. A 10-inch piping system was built containing many transparent acrylic plastic sections for viewing purposes. Fish were introduced in the pipe, and the velocity was increased sufficiently to cause downstream fish movement. In the first section of straight pipe, the fish were observed to be swimming facing the flow. After passing through a 90-degree elbow, the fish became disoriented due to the complex flow pattern in the elbow. After the elbow, the fish toppled through the pipe. After emerging from the pipe, the fish swam in strange ways in the holding tanks until they had regained their equilibrium. Their performance was analogous to the behavior of humans after they become dizzy.

Screens & Louvers

As part of the overall study, screen and louvered types of guidance structures were first studied in the 3- by 3-foot flume in the basement of Alden Building 2. Tests were performed using all three species of fish, which were collected after going through a bypass at the end of the structure. After the success of the small flume, an outdoor facility using vertical axial pumps and a large indoor flume using a ship bow thruster were built to study full-scale guidance systems at prototype velocities. Systems for the Nine Mile Point Project, as well as the Indian Point Project, were investigated in these facilities. In the outside facility, a screen, angled at 25 degrees to the flow, led to a 6-inch vertical bypass opening. From here, the fish entered a 12-inch pipe to a collection area. A weir type gate in this area controlled the flow, and a lift basket collected the test fish. In any one test, roughly a few hundred to a thousand fish were introduced upstream of the screen and went through the bypass area.

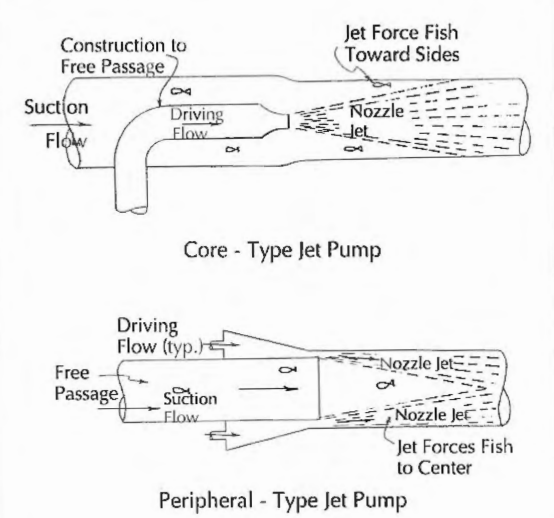

FIGURE 21. A comparison of core-type and peripheral-type jet pumps in relation to potential injury to fish.

There was concern about trash accumulation on the screen guidance systems. Studies using real trash were performed to investigate this question. Trash was measured by weighing, after which it was introduced upstream of the angled screen. After reaching steady state, the trash that remained on the screen and that went through the bypass was weighed and recorded.

After studying the various components of a fish guidance system, they were assembled into the complete system and tested. The system consisted of the angled screen, the bypass, the jet pump, the piping and the collection area. These tests revealed nothing different than what was found when the components were tested alone. However, a major general outcome of all the studies was the effectiveness of the angled, flush-mounted traveling screen with a number of species. A bypass pipe with a jet pump was the preferred means to transport the fish back to their environment.

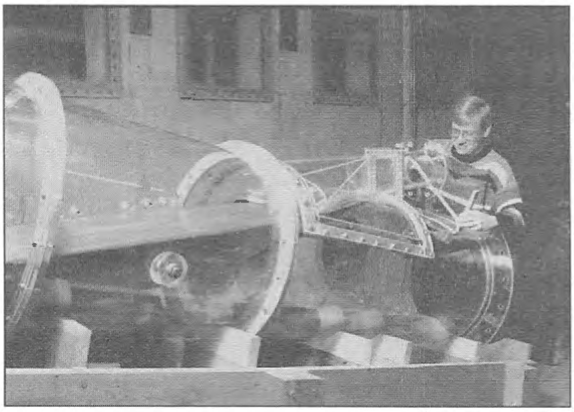

FIGURE 22. Model for screen bypass tests.

Eicher Type Screen & Intake

While some of these studies were being conducted at Alden, George Eicher was designing a fish bypass system for downstream fish migrants at the T.W. Sullivan Plant on the Willamette River in Oregon. Lacking room in the forebay for a traveling screen, Eicher decided that his only alternative was to place an inclined screen in the 11-foot diameter penstock. The screen was made of wedgewire and was inclined at a slope of 19 degrees to the penstock axis. A bypass pipe was installed at the downstream end of the screen to collect fish and any debris, such as trash. The design proved to be a success, and Eicher patented the system. In 1992, Alden conducted a model study to improve the screen geometry near the bypass and to streamline the bypass itself. A photo of the model with the improvements is shown in Figure 22.

The original prototype screen was installed in Washington State at the Elwha Hydroelectric Project. This screen had undergone model testing at another laboratory prior to being installed in a 9-foot penstock in Elwha. In the spring of 1989, the screen was 99 percent effective in bypassing downstream migrating coho salmon smolt. The purpose of the Alden study was to reduce the peak value of the velocity component perpendicular to the screen and to minimize the head losses through the screen, by means of a possible re-design.

The Elwha Eicher screen was inclined at 16.5 degrees to the penstock and contained what is called a screen break at the upper 20 percent of the diameter. At this point, the screen had a –3-degree slope that ended in a bypass pipe. The approach penstock to the screen was not straight. It had a 16-degree bend approximately 3.8 diameters upstream of the screen, causing the approach flow to be asymmetrical. The Elwha screen, made of wedge wire, had three different porosities along its length. The porosity of the upstream portion was 63 percent open. At approximately 60 percent of its length, the porosity was 32 percent open, and after the screen break, the porosity was 8 percent open. The porosity was varied with the intent to improve the velocity distribution along the screen and thereby reduce fish impingement. The results of the model study indicated that a flat, uniform 50 percent porosity screen, with a re-designed simplified straight geometry bypass, satisfied all the requirements with less head loss and an improved velocity distribution.

During the model study, an error was uncovered in the as-built bypass compared to the drawings. The as-built bypass entrance was larger than the drawings called for, resulting in a larger bypass flow. Since the model was constructed from the drawings, model studies were done to see the effect of the change in the entrance.

Modular Inclined Screen

The Eicher screen was designed primarily to be used in an existing penstock at sites where there are no other physical means to bypass downstream migrating fish. In locations where there are no penstocks, a device called a modular inclined screen (MIS) can be utilized to bypass fish. An MIS consists of a streamlined entrance, a wedge wire screen set at a shallow angle to the flow (basically an angled screen) and a bypass to divert fish to a transport pipe or to a holding facility. The screen is set on an eccentric pivot shaft so that it can be rotated for cleaning by backflushing (see Figure 23). The MIS would be installed as a pre-assembled module directly in front of one intake bay, and fish would be guided to this intake.

MIS studies were performed at Alden in 1993. Three different test facilities were used to study various features of the MIS. A small flume was used to measure upstream and downstream velocities adjacent to the screen inclined at angles of 10, 15 and 20 degrees to the flow and with porosity of 30 and 50 percent open. A 1:6.6 hydraulic model was used to study entrance effects, overall head losses and bypass configurations. A third facility, with a 1:3.3 scale of the entire MIS system, was used to evaluate fish reaction, diversion efficiency, immediate fish damage and possible delayed mortality. The three models showed that with relatively uniform approach velocities of 2 to 10 feet per second, the MIS had favorable hydraulic characteristics for fish.

Protection of Fish Larvae

Smolts and larger fish undergoing upstream and downstream migrations at power sites were not the only concerns of environmentalists and regulatory agencies. Fish larvae were studied at Alden from 1978 to about 1980. The purpose of the studies was to investigate several components of fine-mesh screening systems to determine their potential for collecting, diverting or transporting fish larvae with resulting low mortality. The larvae used in these studies were striped bass, alewife, winter flounder and yellow perch. Walleye, channel catfish and bluegill larvae were also used in 1979. The holding facilities were similar to those used in the smolt studies but of smaller size. The holding tanks were either small aquariums or large beakers set in styrofoam.

In all, some 1,500 studies were conducted to determine the mortality of larvae in different systems. The systems were classified into three groups:

- Modified, traveling water screens with fine-mesh screening, lifting buckets and low pressure sprays;
- Angled, traveling water screens with fine-mesh material and a bypass; and,
- Pumping units, jet and mechanical pumps used to return collected or diverted larvae to their natural environment.

Screen retention studies were conducted with flow velocities ranging from 0.5 to 2.0 feet per second and with mesh sizes from 0.014 to 0.079 inches. Larvae size measurements were made on a sample of 25 larvae for each of these tests. It was determined that screen retention was a function of mesh size relative to larval

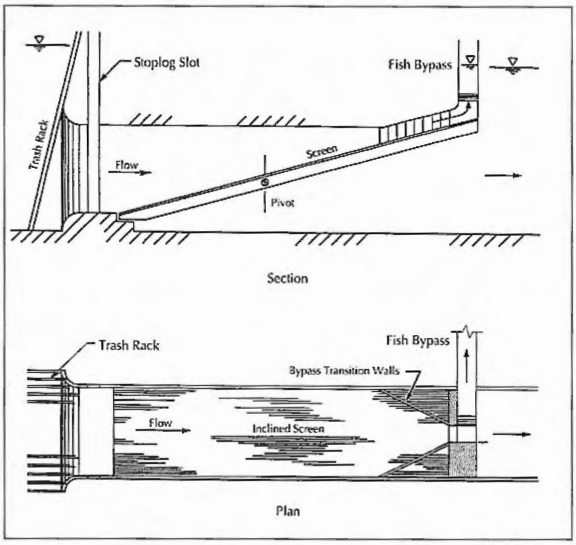

FIGURE 23. Plan and section views of a modular inclined screen.

length and body depth. For some species, a mesh size of 0.02 inches or less might be required to retain all larval stages.

Larvae were also subjected to air exposures, and their mortality evaluated from one to four days. These studies indicated that exposure time was extremely significant in larval mortality, and that air exposures of larvae for any reason should be minimized at all facilities.

As far as diverting larvae, angled fine-mesh screens have the potential to divert older larvae to bypasses, providing the proper mesh size and flow velocity are incorporated in the system. However, it was recommended that studies be conducted for each site prior to selecting the method of handling the larvae.

The jet and screw impeller centrifugal pumps acted differently with the various larvae species. The jet pump was very effective in pumping the striped bass larvae, while the centrifugal pump did a better job with alewife and yellow perch larvae. Once again, the conclusion was to conduct pretests before specifying a pumping system.

Divestiture of Alden Laboratory by WPI

Starting in the 1960s, the United States became a more litigation-minded nation. At all levels in government and private life, lawsuits became a major concern, particularly for those with "deep pockets." By the 1980s, some communities were closing pools and playgrounds due to liability/litigation concerns. In this atmosphere, because Alden's projects involved mega projects, WPI became acutely concerned with liability, even though Alden had never been sued.

On October 17, 1985, while the large Lock and Dam No. 13 navigation model and others were in "full swing," the WPI errors and omission insurance on the Alden Research Laboratory and the Manufacturing Engineering Application Center (MEAC) terminated. WPI chose not to renew the Alden policy due to its high cost, even with a large deductible. Later, directed by the WPI trustees, the school's president and the vice president of business affairs negotiated with the Alden director and four Alden senior engineers to divest the world-renowned facility even though it had the largest WPI research budget.

In April 1986, the final agreements were signed by both sides, making Alden a private for-profit company. The five new owners who bought the business and the equipment were Albert G. Ferron, George E. Hecker, Johannes Larsen, James B. Nystrom and Mahadevan Padmanabhan. Hecker was voted president of the new corporation. One of the sale conditions was the retention of the Alden name by the new company. On May 12, 1986, the laboratory officially began as a new private company under the name of Alden Research Laboratory, Inc. — the fifth name for the laboratory since its inception. The names and the year they changed were as follows:

Hydraulic Testing Laboratory (1894)
Alden Hydraulic Laboratory (1915)
Alden Research Laboratories (1965)
Alden Research Laboratory (1977)
Alden Research Laboratory, Inc. (1986)

GEORGE E. HECKER *was appointed Director of the Alden Research Laboratory in 1975, when it was part of WPI, and became President in 1986 when Alden was separately incorporated. Prior to joining Alden in 1971, he worked for Stone & Webster in Boston and for the Tennessee Valley Authority before that. With more than 35 years of experience in solving flow problems using physical models, analyses and field studies, he has published widely and has served on many national professional committees. He has degrees from Yale and the Massachusetts Institute of Technology.*

ALBERT G. FERRON *was employed at Alden for 35 years. He also was an Adjunct Associate Professor of Mechanical Engineering at WPI. Upon his retirement from Alden in 1992, he was Vice President of the Flow Meter Calibration Section. Currently, he is employed at the University of Massachusetts Medical School in Worcester, continues as an Adjunct Associate Professor in WPI's Department of Civil & Environmental Engineering and is active in many community projects.*

BRUCE J. PENNINO *is Professor of Civil Engineering Technology at Springfield Technical Community College. Formerly, he was a Research Engineer at Alden for many years. He has a B.S.C.E. from Bucknell University and a M.S.C.E. from Colorado State University. He has over 30 years of civil and hydraulic engineering experience, and is a registered professional engineer in Massachusetts.*

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